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Special Issue Reprint

Feature Papers to Celebrate the Inaugural Issue of *Standards*

Edited by
Peter Glavič

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Editor

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About the Editor

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Peter Glavič graduated in Chemical Technology, and later in Economics and Business. He earned his Master's and Doctoral degrees in Chemistry. Prof Glavič has held managerial positions in the paper, chemical, ceramics, and metallurgical industries for 9 years. He served as a Professor of Chemical Engineering for 30 years. His research focused on process systems engineering, environmental engineering, education, and sustainable development. He participated in many international research projects financed by EU, NATO, national agencies, companies, etc. He has published more than 120 scientific articles, 110 papers at international conferences, 85 scientific and 140 professional reports, and 20 textbooks. Prof Glavič has more than 3200 citations and a h-index of 24. He was a member of the Slovenian Parliament for 8 years, vice-rector, president of the Slovenian Academy of Engineering, chairman of several professional bodies in Slovenian Chemical Society, the Society of Economists in Maribor, and the University Centre for professor emeriti and retired professors. He is Editor-in-Chief of MDPI Standards journal, Guest Editor of Processes, and a Member of Editorial Board in some other journals. He has been a member of many international scientific committees, professional bodies, etc.

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Editorial

Special Issue: Feature Papers to Celebrate the Inaugural Issue of *Standards*

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We are glad to present the inaugural issue of the *Standards* journal. The journal is a scientific journal on standardization, assessment, verification, inspection, certification, testing, quality control, rating, and all other related topics. It covers all scientific, engineering, and technology fields.

Standards can be international (ISO, IEC, WHO, EN, etc.), national (ASTM, DIN, BS, UNE, etc.), regional, or corporate ones. They cover production and consumption: management systems, security management, risk management, anti-bribery management systems, energy management, life cycle assessment, environmental management, social responsibility, occupational health and safety, food safety management, quality management, quality control, testing and calibration laboratories, quantities and units, and diverse devices and equipment, to mention the most popular ones [1]. They are basic for our everyday activities: ambient air and water quality, information security, date and time format, currency codes, country codes, language codes, and medical devices. International Accounting Standards (AS), International Financial Reporting Standards (IFRS), and 30 ISO standards, related to COVID-19, etc., exist [2].

In spite of the great number of different standards, new ones are appearing daily. The standardization process includes development, acceptance, and implementation of new or improved standards. The stakeholders can include companies, standardization institutions, governments, users, interest groups, professionals, and scientists. The International Organization for Standardization, ISO, has a guidance document on new work with three parts: (1) new standardized areas, (2) new fields of work, and (3) new work item proposals within existing committees [3]. New standards need to be inspected and verified, their quality has to be assessed, and they can be improved if found suitable.

Besides the technical standards, other standards, norms, conventions, and requirements exist, e.g., credentials, certificates, patents, permits, etc. They are improving quality, reliability, efficiency, durability, and other properties of goods and services. They can be voluntary or obligatory, and used internally or externally.

A rapid development of standards is expected in the future. Climate change, with the planned carbon neutrality by 2050, population growth, and demographic trends will require rigorous changes in the way we live, eat, dress, travel, and produce and use energy. Scarce raw materials and renewable energy sources will demand higher energy efficiency and a circular economy with materials reuse. Standardization will play an important role in process and product design, production, distribution, consumption, and recovery.

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Editorial

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Standards are a set of guidelines or criteria used to ensure consistency, quality, safety, and compatibility in products, services, and processes. They provide a basis for testing, inspecting, and certifying products and services.

Companies can use various kinds of standards, including international standards such as ISO (International Organization for Standardization), national standards such as ASTM (American Society for Testing and Materials), regional standards, and corporate standards. These standards cover a wide range of topics, such as management systems, risk management, energy management, environmental management, social responsibility, quality management, and testing and calibration laboratories.

New standards are continuously emerging due to the changing needs of the industry, advances in technology, and global events such as pandemics and climate change. For example, in response to the COVID-19 pandemic, the ISO developed 30 standards related to COVID-19. As we face climate change and the need for sustainability, new standards related to energy efficiency, the circular economy, and environmental management are likely to emerge.

Standards are necessary because they provide a common language and framework for companies, governments, and other organizations to communicate and work together. They help to increase efficiency, improve quality, and reduce costs. Standards also provide a level of assurance to customers and stakeholders that products and services meet certain requirements and expectations.

Climate change and sustainability are closely connected to standards. The development and implementation of standards related to energy efficiency, renewable energy, and environmental management can help companies reduce their environmental impact and contribute to a more sustainable future. Standards also provide a framework for measuring and reporting on progress towards sustainability goals.

Being aware of the importance that standards have for the human society in general, and specifically for individuals, consumers, companies, institutions, governments, etc., MDPI (Multidisciplinary Digital Publishing Institute) established the journal *Standards* in 2021. *Standards* is an international, peer-reviewed, open access journal on standardization, inspection, verification, certification, testing, and quality control published quarterly online.

The first paper was published in *Standards* in May 2021 and the second one in August. Altogether, there were 12 papers published in 2021 and 39 in 2022. The most popular paper in 2021 has 4014 views and the top one published in 2022 has 3225 views. The most cited paper published in 2021 has seven citations so far, and the most cited in 2022 has 9 citations already. They are indexed by DOAJ (Directory of Open Access Journals). There are 102 Editorial Board members, 72 of them coming from the European Union member states.

Two Special Issues were organized in 2021, and eight of them had three additional topic titles in 2022. The present Special Issue (https://www.mdpi.com/journal/standards/special_issues/Inaugural_Issue accessed on 31 March 2023) is the inaugural Issue of this journal, with 29 papers in total. We thank all of the authors, reviewers, and members of the Editorial Board for facilitating the successful start of the *Standards* journal.

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Special Issue Overview

In today's world, where sustainability, innovation and quality are the key success factors, the need for standardization has become increasingly important for many reasons, including promoting innovation, improving quality, ensuring safety and sustainability, reducing costs and increasing efficiency [1]. In this journal, we compile a collection of articles that address various aspects of standardization, its challenges and benefits. From the quality of products and services to the protection of the environment, standards play a critical role in shaping the future of businesses and societies alike [2]. In this journal, each article offers valuable insights into the role of standardization in promoting sustainable and innovative practices in different sectors. We hope that the articles will be of interest to researchers, practitioners, and policy makers in the field of standardization.

The development and implementation of standards presents various challenges, including technological and socio-economic factors [3]. In addition, the language barrier is another challenge in implementing standards [4].

Voluntary sustainability standards (VSS) are gaining momentum and are being adopted by more and more organizations [5]. Companies using quality and innovation management systems face the challenge of integrating them [1,6,7].

New technologies and processes require standardization to enable the seamless interaction of different technologies, to facilitate the integration of different applications and services, and to foster innovation, e.g., in the development of smart cities [8,9]. Manufacturers can demonstrate the quality and performance of their products, which in turn increases confidence in the construction industry and ultimately leads to a better and safer built environment [10–14].

Standardization also played a crucial role in developing effective measures and strategies in response to the pandemic [3]. In the field of medicine, standards can help establish best practices, improve accuracy and consistency, and enable fair, objective decision making processes [15–18].

The use of standardized definitions and units helps to ensure consistent and accurate measurements across countries and territories [19–22]. In chemical and environmental engineering, this is essential to ensure the safety and health of the public and the environment [23,24]. In science education, teachers must have the competence and confidence to integrate science and engineering practices into the classroom [25].

In summary, standardization can facilitate the sharing of data and best practices among stakeholders, thus promoting the adoption of more sustainable practices [19]. As science and technology continue to advance, the need for standards and guidelines will only increase [26–29].

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Review

Review of the International Systems of Quantities and Units Usage

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Abstract: The International System of Quantities has to be used by scientific and engineering journals as well as by authors of their articles, conference papers, and corresponding books, especially textbooks. This paper describes the historical development and the state of the art of international communications in science, engineering, technology, production, and sustainable development. The International System of Quantities (ISQ) which systematically elaborated on the standards of the International Organization for Standardization and International Electrotechnical Commission on quantities and units (ISO/IEC 80000) still needs to be generally accepted and used. The list of standardized base and derived quantities with their symbols, and rules for terminology of other quantities are presented. In addition, names and symbols of base, derived, and "compound" units for these quantities are given. The most frequent mistakes and some recommendations about the use of quantities, units, prefixes, quantity value expressions, numbers, and symbols of chemical elements are shown, too. The standards shall be available in open access. The lack of standardized quantities regarding science, engineering, and economics is drawn to attention. Further development of the international systems of quantities and units could bring substantial synergies worldwide.

Keywords: quantities; units; symbols; standard; mistakes

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1. Introduction

Alphabetic writing started three millennia ago in the Sinai peninsula, and continued in ancient Phoenicia, Israel, Greece, and Italy. The Latin alphabet was developed in the Roman Empire and its symbols and letters have been changing over the last millennium but they have become the main global script today. They are used not only in Western and Central Europe, North and South America, and Australasia but also in Central and South Africa, and in some countries of Asia. Today, Greek letters are still used in Greece, and in science and engineering.

World languages evolved mostly with empires; ancient Greek and Latin languages are most known but also Chinese, Persian, Arabic languages became widespread. In modern ages Spanish, English, French, and Russian languages became internationally used. Today, about 1.2 G (billion) people speak native Chinese, 1.1 G English, 0.8 G Indo-Aryan, and 0.5 G Arab languages. Latin and Arab languages are still used worldwide for religious purposes but in the 19th century French and in the 20th century English has overtaken world communications in international relations, business, commerce, science, and education.

A similar development occurred with numbers and their symbols—numerals. The Egyptians had been the first to use the ciphered numeral system, followed by Greeks' numbers and the Roman numeral system which had combined several letters of the Roman alphabet (I, V, X, L, C, D, and M) into numbers which were used in Europe until the end of the 14th century when the Hindu-Arabic numeral system started to substitute them; it spread out to the whole world at the present. However, Roman numerals are still used, e.g., in denoting centuries, months, and the 21 cards (trumps) in the tarot game.

Weights and measures were the next groups that evolved with human development. A unit of measurement was agreed upon, most often imposed by a national sovereign or international emperor. In the beginning, the measures were based on the human body, e.g., inch, foot, or natural phenomena, e.g., day, year. Various definitions existed in different countries, e.g., for a pound—it originated from the Roman libra (abbreviated as lb); an international agreement about the value of a pound was accepted as late as 1959 (1 lb = 0.453 592 37 kg, exactly). The multiplier was most often the number 12, e.g., 1 ft = 12 inches, 1 foot is equal to 12 inches, as it was easily divided by 2, 3, and 4.

1.1. The International System of Units

The French revolution brought up the metric, decimal system. It was initiated in 1792 and the first prototypes of metre and kilogram were standardized in 1799. In 1861 coherent measurement units were introduced with the units of length (centimetre), mass (gram), and time (second). In 1875 the Metre Convention (Convention du Mètre, also known as Treaty of the Metre) was signed by 17 member states. The following international organization and its two bodies were formed:

- The General Conference on Weights and Measures (Conférence Générale des Poids et Mesures, CGPM),
- The International Committee for Weights and Measures (Comité International des Poids et Mesures, CIPM) and,
- The International Bureau for Weights and Measures (Bureau International des Poids et Mesures, BIPM).

In 1901 the CGPM declared a kilogram as a unit of mass, not of weight. In 1960, the CGPM accepted the International System of Units (**S**ystème **I**nternational d'Unités, SI [1]) with four additional "base units" to metre and kilogram: second for a time duration, ampere for electric current, kelvin for thermodynamic temperature, and candela for luminous intensity; 16 "derived units" with special names were accepted, too. The seventh base unit, mole for amount of substance was accepted by the CGPM in 1971. Six additional derived units with special names have been gradually adopted, bringing their number to 22. The SI base units have been redefined several times and the last time took place in 2018 following Feller's proposal [2] of using "exact numerical values for seven defining constants expressed in terms of their SI units" (1, pp. 127–135); e.g., "the metre was redefined in terms of the speed of light, and the second was redefined based on the microwave frequency of a caesium atomic clock". In the European Union (EU), the SI acceptance and adaptations are being led by the European Commission, and its directives are realized by member states.

Today, SI is prevailing in the world, only Myanmar (Burma) and Hong Kong are not using it. The UK and USA are still predominantly using the old English system with the UK imperial units and US customary units, respectively, besides the SI (the so-called hybrid system); they are used in general public but not in science, engineering, medicine, and many industrial companies—especially not in multinational ones. Besides, they have been defined exactly by the SI units. The United States National Institute of Standards and Technology, NIST, has adopted and published the SI [3].

Symbols of base units and derived units with special names have been developed in parallel with the metric units and are now well established. The SI system also provides twenty prefixes to the unit names and unit symbols that may be used when specifying power-of-ten (i.e., decimal) multiples or submultiples of SI units.

1.2. The International System of Quantities—ISQ

The system of quantities was the last to be developed and standardized globally. Quantity is a property of a phenomenon, body, or substance, where the property has a magnitude that can be expressed by means of a number and a reference (unit). The first international organizations trying to adopt chemical and physical quantities were the International Union of Pure and Applied Physics, IUPAP (established in 1922) and the International Union of Pure and Applied Chemistry, IUPAC (formed in 1919). IUPAP prepared its first edition of *Symbols, Units and Nomenclature in Physics* in 1961—for official use only [4]; its 1987 revision is available online [5]. IUPAC published the first edition of the *Manual of Symbols and Terminology for Physicochemical Quantities and Units* in 1969 [6]. After the 3rd edition they changed the title of the manual and published it as the Green Book, again with three editions [7]. The Green Book is available on Internet, too.

In 1988, the International Organization for Standardization, ISO, in cooperation with the International Electrotechnical Commission, IEC, published the first edition of the international standard ISO 31 *Quantities and units* in 14 parts [8], and ISO 1 000 SI units and recommendations for use [9]. In 1992 both standards were substituted by ISO 80000 Quantities and units containing 13 somewhat reorganized parts; the last edition was published in 2019 with the exception of the parts mentioned in parentheses [10]:

1. General (2009)
2. Mathematics
3. Space and time
4. Mechanics
5. Thermodynamics
6. Electromagnetism (2008)
7. Light and radiation
8. Acoustics (2020)
9. Physical chemistry and molecular physics
10. Atomic and nuclear physics
11. Characteristic numbers
12. Condensed matter physics
13. Information science and technology (2008)

The general part contains information about quantities and units, printing rules, rules for terms in names for physical quantities, rounding of numbers, logarithmic quantities, and international organizations in the field. In parts 3–13, the quantities of each subset are listed including: item number, quantity name, symbol and definition, unit symbol, and eventual remarks. Each part has an alphabetical index of quantities at the end to enable searching the items. Most of the parts have been updated in 2019 and 2020 with the exception of parts 1 (2009), 6 (2008), 13 (2008), and 14 (2008, withdrawn); the first two of them are planned to be updated in the year 2021.

In 1984 the first edition of the *International vocabulary of basic and general terms in metrology* was published by the ISO [11]. The Joint Committee for Guides in Metrology (JCGM) was formed in 1997 by seven International Organizations: BIPM, IEC, the International Federation of Clinical Chemistry and Laboratory Medicine (IFCC), ISO, IUPAC, IUPAP, and the International Organization of Legal Metrology (OIML); in 2005, the International Laboratory Accreditation Cooperation (ILAC) officially joined the seven founding international organizations. JCMG prepared the International vocabulary of basic and general terms in metrology (VIM)—its third edition (2008) with small corrections (2012) is available on the Internet [12]. It includes English and French terms of quantities and units, measurements, devices for measurement, properties of measurement devices, and measurements standards (Etalons).

After having worldwide acceptable letters, numerals, and measurement units we have already had for some decades the International System of Quantities (ISQ), which was legally accepted by members from 165 countries (including the UK and USA). The authors of scientific journals and journal lectors shall use the International System of Units (SI) for all dimensional quantities, and respect the ISO 80000 standard rules on the names and symbols of quantities and units. ISQ is still developing—we are urgently missing rules for quantities in some additional fields, e.g., in chemical engineering and economics.

Many mistakes exist that authors of scientific papers and articles do not pay attention to in the SI and ISQ systems. Even most international journals do not require the authors to use ISQ rules; the author's corrections which are respecting the ISO rules may even be changed during the final corrections into wrong printing. All scientists and engineers (mechanical, chemical, electrical, civil, textile, metallurgical, etc.) need to talk the same language (terminology) and use the same symbols for quantities and units to understand each other and avoid crucial mistakes. That is why the international standard on quantities and units is essential; every one shall respect it and its principles, not use "field languages". Universities are expected to respect the rules of ISO 80000, teach and apply the legal nomenclature thus making the students' knowledge acquisition easier. It is difficult for students if the lecturers of different courses, e.g., in physics or chemistry and engineering are using different names, symbols, and units for the same physical or chemical quantity—often they miss the synergy of using the same name, symbol, and unit. The same is true for the terminology used in scientific and professional journals, conference proceedings, books, and manuals. Besides that the SI and ISO standards:

- Ensure that products and services are safe, reliable and of good quality;
- For business, they are strategic tools that reduce costs by minimizing waste, losses, and errors and increase productivity; they help companies to access new markets, level the playing field for developing countries, and facilitate free and fair global trade.

In the following sections, the most important rules from the SI Brochure [1] and ISO 80000-1 [10], and the most common mistakes regarding quantities, dimensions, measurement units, numbers, and printing rules will be explained. The article brings practical advice on how to use agreed upon names and symbols of quantities, and reduce the mistakes and time losses that arise when using different names and symbols for the same quantity.

2. Quantities

2.1. Quantity Names and Definitions

ISQ contains 7 base quantities and 22 derived quantities with special names of their units. Derived quantities are defined in terms of base quantities. The parts of ISO 80000 cite 715 quantities and 238 mathematical items. This is far from the number of quantities used today. As mentioned before, some engineering and economic fields are completely missing. Therefore, we have to respect the nearly 1 000 of those agreed upon. Besides that, the ISO 80000-1 presents some norms to names of physical quantities (Table 1). The most often occurring mistakes are misuse of terms coefficient and factor, (amount of substance) concentration and mass concentration, molarity and concentration, mass and weight, (mass, volume, amount of substance, and number) ratios and fractions. Ordinal properties, such as Rockwell hardness, and nominal properties, such as the colour of light, are not a part of the ISQ.

Here are more elaborate explanations of the quantities in Table 1:

- The term "coefficient" should be used when two quantities A and B have different dimensions, e.g., linear expansion coefficient α_l, $\mathrm{d}l/l = \alpha_l \,\mathrm{d}T$—its unit is not equal to 1; sometimes, the term "modulus" is used instead of the term "coefficient", e.g., modulus of elasticity E, $\sigma = E\varepsilon$.
- The term "factor" should be used when the two quantities A and B have the same dimension, e.g., friction factor, μ, $F = \mu F_\mathrm{n}$; its unit is 1.
- The adjective "specific" is added to the name of a quantity to indicate the quotient of that quantity by mass, e.g., specific heat capacity c, $c = C/m$; specific volume v, $v = V/m$
- Combination of quantities which occur in equations are often considered to constitute a new quantity called "parameter", e.g., Grüneisen parameter γ, $\gamma = \alpha_V/(kc_V\rho)$.
- The quotient of two quantities of the same dimension is often called "ratio", e.g., ratio of specific heat capacities γ, $\gamma = c_p/c_V$; its unit is 1;
    - The term "index" is sometimes used instead of ratio, e.g., refractive index n, mboxemphn $= c_0/c$
    - The term "fraction" is used for ratios smaller than one, e.g., mass fraction of a substance X, w_X, $w_\mathrm{X} = m_\mathrm{X}/m$; amount of substance fraction x_X, y_X, $x_\mathrm{X} = n_\mathrm{X}/n$;

volume fraction φ_X, $\varphi_X = x_X V_{m,X}/(\Sigma_i\, x_X V_{m,i})$ ($V_{m,X}$ being molar volume); their unit is 1;

- The term "percentage" shall not be used in a quantity name, because it is misleading; if a mass fraction is 0.78 (w = 78%), is the percentage than 78 or 78% = 0.78? Instead, the unambiguous term (volume, number, time, or amount of substance) "fraction" shall be used; the terms "mole fraction" and "share in %" are deprecated, too.
- The noun "density" is added to the name of a quantity to indicate the quotient of that quantity by the volume, e.g., mass density ρ, $\rho = m/V$; energy density e, $e = E/V$
  - The noun "density" is also used to express a flux or current to indicate the quotient of such a quantity by the surface area, e.g., density of heat flow rate q, $q = \Phi/A$
  - The term "surface . . . density" is added to the name of a quantity to indicate the quotient of that quantity by the area, e.g., surface mass density ρ_A, $\rho_A = \mathrm{d}m/\mathrm{d}A$
  - The term "linear . . . density" or the adjective "linear" is added to the name of a quantity to indicate the quotient of that quantity by the length, e.g., linear mass density or linear density ρ_l, $\rho_l = \mathrm{d}m/\mathrm{d}l$
  - The term "linear" is also added to the name of a quantity, solely to distinguish between similar quantities, e.g., linear expansion coefficient α_l, $\alpha_l = (1/l)(\mathrm{d}l/\mathrm{d}T)$, and cubic expansion coefficient α_V, $\alpha_V = (1/V)(\mathrm{d}V/\mathrm{d}T)$
- The adjective "molar" is added to the name of a quantity to indicate the quotient of that quantity by the amount of substance, e.g., molar volume V_m, $V_m = V/n$; molar mass M, $M = m/n$.
- The term "concentration" is added to the name of a quantity to indicate the quotient of that quantity by the total volume, e.g., amount of substance (B) concentration c_B, $c_B = n_B/V$; mass concentration ρ_B, $\rho_B = m_B/V$; number (particle or molecular) concentration C_B, $C_B = N_B/V$; in chemistry, the name "amount of substance concentration" can be abbreviated to "concentration" or replaced by specifying the substance, e.g., concentration of benzene, but the adjective "mass" should never be omitted from the name "mass concentration". "Molarity" with a symbol M and the unit mol/L shall be avoided—use (amount of substance) concentration and the symbol c.

Table 1. Terms in names for physical quantities.

Term	Definition	Examples			
		Name	Symbol	Defining eq.	Unit
coefficient	quotient of quantities with different dimension	linear expansion coefficient diffusion coefficient Hall coefficient	α_l D A_H	$\mathrm{d}l/l = \alpha_l\,\mathrm{d}T$ $J = -D\,\nabla n$ $E_H = A_H(B \times J)$	1/K m^2/s m^3/C
factor	quotient of quantities with the same dimension	friction factor quality factor thermal diffusion factor	μ Q α_T	$F = \mu F_n$ $X = QR$ $\alpha_T = k_T/(x_A\, x_B)$	1 1 1
specific	divided by mass	specific heat capacity specific volume	C v	$c = C/m$ $v = V/m$	J/(kg K) m^3/kg
ratio, index	quotient of two quantities of the same dimension	heat capacity ratio mass ratio of B and A volume ratio of B and A refractive index	γ ζ ψ n	$\gamma = c_p/c_V$ $\zeta = m_B/m_A$ $\psi = V_B/V_A)$ $n = c_0/c$	1 1 1 1
fraction	ratio, smaller than one	mass fraction amount of substance fraction volume fraction	w_X x_X, y_X φ_X	$w_X = m_X/\Sigma m$ $x_X = n_X/\Sigma n$ $\varphi_X = V_X/\Sigma V$	1 1 1
density	divided by volume	mass density	ρ	$\rho = m/V$	kg/m^3
molar	divided by amount of substance	molar volume molar mass	V_m M	$V_m = V/n$ $M = m/n$	m^3/mol kg/mol
concentration, mass concentration	divided by volume	concentration of B mass concentration of B	c_B ρ_B	$c_B = n_B/V$ $\rho_B = m_B/V$	mol/m^3 kg/m^3

Ordinal properties are defined by a conventional procedure, for which a total ordering relation can be established, according to magnitude, but no algebraic operations among these properties exist. They have neither measurement units nor quantity dimensions. Ordinal properties are arranged according to ordinal scales. Some examples are: Rockwell C hardness, octane number for petroleum fuel, earthquake strength on the Richter scale.

The nominal property of a phenomenon, body, or substance has no magnitude but it has a value, which can be expressed in words, by alpha-numerical codes, or by other means. Some examples include: sex of a human being, the colour of a paint sample, ISO two-letter country code, the sequence of amino acids in a polypeptide.

2.2. Symbols for Quantities

Symbols for quantities are generally single letters from the Latin or Greek alphabet, sometimes with subscripts or explanations in parentheses. Symbols for characteristic numbers are written with two letters, the initial of which is always a capital, e.g., Ma for Mach number.

The quantity symbols are always printed in italic (sloping) type irrespective of the type used in the rest of the text—italics are used automatically with the Equation Editor. On the other side, the symbols of units are printed in roman type. Therefore, m means metre while m stands for mass. A subscript that represents a physical quantity or a mathematical variable, such as running number, is printed in italic (sloping) style, e.g., $\mathrm{C_p}$ (p: pressure), $\mathrm{c_i}$ (i: running number), but $\mathrm{\mu_r}$ (r: relative), $\mathrm{S_m}$ (m: molar). The e or exp as a base of natural logarithms is printed in roman. The same is true for the constant π (Ludolf number), and for mathematical symbols in expressions lg x, ln x, min(a, b), max f(x), lim f(x), sin x, sinh x, erf x, etc.

When symbols for quantities are combined in a product of two or more quantities, this combination is indicated in one of the following ways: ab, a b, a · b, e.g., $\mathrm{-r = kc_A c_B{}^2}$. Division of one quantity by another is indicated in one of the following ways: $\frac{a}{b}$, a/b, $\mathrm{a\ b^{-1}}$, $\mathrm{a \cdot b^{-1}}$; the solidus (/) can be substituted by a horizontal bar. Do not write $\mathrm{ab^{-1}}$, without a thin space between a and $\mathrm{b^{-1}}$, as $\mathrm{ab^{-1}}$ could be misinterpreted as $\mathrm{(ab)^{-1}}$. Parentheses shall be used in more complex expressions, e.g., a/(b · c), (a · b)(c + d).

Authors often do not distinguish between symbols of quantities and acronyms. Acronyms are abbreviations, usually formed from the initial letters of a group of words, e.g., BTC for the "blow-down treatment cost". They are printed in roman type and they shall not be used in equations. Symbols and abbreviations shall be explained when used for the first time if further usage is planned. Also, a list of quantity symbols (with names and units) and acronyms shall be presented.

ISO 80000 does not cover fields of economics, operational research, or statistics. Economists often use acronyms instead of single-letter symbols for economic quantities, even in equations, e.g., NPV for net present value, IRR for internal rate of return. In accordance with ISO 80000-1 rules, we suggest using the following symbols for economic quantities: C for cost, D for depreciation, E for expenses, $\mathrm{F_C}$ for cash flow, i for interest rate, $\mathrm{I_{FC}}$ for fixed capital investment, N for number, $\mathrm{R_{IR}}$ for internal return rate, S for sales, $\mathrm{t_{pb}}$ for payback time, $\mathrm{V_B}$ for book value, $\mathrm{V_{NP}}$ for net present value (or worth), etc.

2.3. Frequent Mistakes

Frequent mistakes connected with names of quantities are:

Quantities shall be clearly defined, e.g., mass fraction of sodium, w(Na) or w_{Na}, or its amount fraction, x(Na) or x_{Na}.

- Specification of quantities, e.g., chemical oxygen demand is a part of the name of a quantity, it is not a part of the unit (mass concentration of O_2 in mg/l, not mg O_2 per litre).
- "Amount (of substance)" is a chemical quantity expressed in moles; therefore, the word is not to be used for values in general (e.g., amount of heat)—be specific (use e.g., volume, mass, amount of substance, number, heat) or use magnitude, value, or contents as a general term.

- Velocity is a vector (rate of change of a position vector); speed is the magnitude of a velocity.

Differentiate between:

- Mass, m in kg, and weight F_g in N;
- Mass density or density, ρ or ρ_m in kg/m^3, surface (mass) density, ρ_A in kg/m^2, linear (mass) density, ρ_l in kg/m, and density of heat flow rate, q or ϕ in W/m^2;
- Mass flow rate, q_m in kg/s, and mass flow, $\boldsymbol{j}_m$ in kg/(m^2 s);
- Work, W in J, energy, E in J, heat, Q in J, enthalpy H in J, and pressure, p in Pa;
- Power, P in W, heat flow rate, Φ in W, and enthalpy flow rate, I in W;
- Heat capacity, C in J/K, specific heat capacity, c in J/(kg K), specific heat capacity at constant pressure, c_p in J/(kg K), and specific heat capacity at constant volume, c_V in J/(kg K);
- Depreciation (decrease in value of a property over an estimated period of time, e.g., per year), and amortization (decrease in value when the period of time is definitely known).

Regarding quantity symbols, mind the following mistakes and recommendations:

- Find the right symbol by examining each Index of ISO 80000 parts 3–13 (hopefully, a new edition of ISO Standards Handbook [13] with a joint index will be published soon);
- Any attachment to a unit symbol as a means of giving information about the special nature of the quantity or context of measurement under consideration is not permitted, e.g., P_e = 700 kW, not P = 700 kW$_e$; U_{max} = 500 V, not U = 500 V$_{max}$;
- Do not use different symbols for the same quantity; when, for one quantity, different applications or different values are of interest, a distinction can be made by the use of subscripts, e.g., F_F for an amount flow rate of feed to the distillation column, F_B for bottom product one, F_D for distillate flow rate;
- Do not use two different symbols for the same quantity, e.g., A and S for area;
- Do not use the same symbol for two different quantities instead of two different symbols, e.g., γ for mass concentration (g/L), w for mass fraction, and ζ for mass ratio (e.g., in g/kg);
- Use N for number of entities (not n, which is used for the amount of substance in moles);
- Use q_V for volume flow rate (in m^3/s), but q_m for the mass flow rate (in kg/s).

3. Units

3.1. SI Base Units

The International System of Units (SI) is a set of base units, together with their names and symbols, multiples and submultiples, defined in accordance with given rules. The SI is based on seven base quantities (Table 2). In each coherent system, there is only one base unit for each base quantity, e.g., in the SI, the metre is the base unit of length. Symbols representing the dimensions of the abase quantities in the ISQ are also presented; they are printed in single upper case letters in roman, sans serif type, e.g., Calibri, Helvetica, but not Times New Roman.

Table 2. Seven International System of Quantities (ISQ) base quantities, their International System of Units (SI) base units, and quantity dimensions.

ISQ Base Quantity		SI Base Unit		Symbol for Dimension
Name	**Symbol**	**Name**	**Symbol**	
length	l, L	metre	m	L
mass	m	kilogram	kg	M
time duration	t	second	s	T
electric current	I, i	ampere	A	I
thermodynamic temperature	T, Θ	kelvin	K	Θ
amount of substance X	$n(\mathrm{X})$	mole	mol	N
luminous intensity	I_v	candela	cd	J

3.2. SI Derived Units

A derived unit is a measurement unit for a derived quantity; for example, the metre per second, symbol m/s, and the centimetre per second, cm/s, are derived units of speed in SI. Coherent derived unit is a product of powers of base units with no other proportionality factor than one; e.g., metre per second is the coherent derived unit for velocity when velocity is defined by the quantity equation $\boldsymbol{v} = \mathrm{d}\boldsymbol{r}/\mathrm{d}t$. The kilometre per hour is not a coherent derived unit in SI. Centimetre per second is also not a coherent derived unit in SI but it is a coherent derived unit in the CGS (centimetre, gram, second) system.

Dimension expresses a derived quantity with the base quantity dimensions as a product of powers of factors corresponding to the base quantities, $\dim Q = \mathrm{L}^\alpha\mathrm{M}^\beta\mathrm{T}^\gamma\mathrm{I}^\delta\Theta^\varepsilon\mathrm{N}^\zeta\mathrm{J}^\eta$, omitting any numerical factor, e.g., the dimension of force is denoted by $\dim F = \mathrm{LMT}^{-2}$. In ISQ, $\dim \rho_\mathrm{B} = \mathrm{ML}^{-3}$ is the quantity dimension of mass concentration of component B, ρ_B, and also the dimension of mass density, ρ. Quantities with the same dimension are named quantities of the same kind. When all exponents of the factors corresponding to a base quantity in its quantity dimension are zero, a quantity of dimension number ("dimensionless quantity") is obtained.

The derived unit for force is kg m/s^2, which is rather inconvenient. Therefore, special names and symbols have been approved for the 22 most common SI-derived units (Table 3)—the last four of them are admitted for reasons of safeguarding human health. Symbols for units consist of one or two letters from the Latin or Greek alphabet. These letters are lower case, except that the initial letter is a capital when the unit is derived from a proper name of a person, e.g., V for volt, A for ampere.

There are some non-SI, non-coherent units that are allowed to be used with the SI (Table 4); the year (symbol a, 1 a = 365.242 20 d = 31 556 926 s) is not included. Atomic and CGS units, imperial and US customary units (foot, pound, and second) as well as the units carat, tex, atmosphere (atm, and at), torr, mmH$_2$O, calories (cal) are deprecated.

Table 3. SI derived units with special names and symbols.

ISQ Derived Quantity		SI Derived Unit		
Name	**Symbol**	**Special Name**	**Special Symbol**	**In SI Base and Derived Units**
plane angle	α,β,γ	radian	rad	rad = m/m
solid angle	Ω	steradian	sr	sr = m^2/m^2
frequency	f,ν	hertz	Hz	Hz = s^{-1}
force	F	newton	N	N = kg m/s^2
pressure, stress	p	pascal	Pa	Pa = N/m^2
energy	E	joule	J	J = N m
power	P	watt	W	W = J/s
electric charge	Q, q	coulomb	C	C = A s
electric potential difference	V_{ab}	volt	V	V = W/A
capacitance	C	farad	F	F = C/V
electric resistance	R	ohm	Ω	Ω = V/A
electric conductance	B	siemens	S	S = Ω^{-1} = A/V
magnetic flux	Φ	weber	Wb	Wb = V s
magnetic flux density	J_m	tesla	T	T = Wb/m^2
inductance	L	henry	H	H = Wb/A
Celsius temperature	t,δ	degree Celsius	°C	°C = K
luminous flux	Φ_v	lumen	lm	lm = cd sr
illuminance	E_v	lux	lx	lx = lm/m^2
activity (of a radionuclide)	A	becquerel	Bq	Bq = s^{-1}
absorbed dose	D	Gray	Gy	Gy = J/kg
dose equivalent	H	sievert	Sv	Sv = J/kg
catalytic activity	ξ	katal	kat	kat = mol/s

Finally, "compound units" can be formed by multiplication and/or division of different base and/or derived units. The SI Brochure lists some examples of SI coherent derived units, dividing them into two groups:

1. Those expressed in terms of base units, e.g., m^3 for volume, m/s for velocity or speed, kg/m^3 for (mass) density or mass concentration, A/m for magnetic field strength, mol/m^3 for the amount of substance concentration, cd/m^2 for luminance, etc.
2. Those whose names and symbols include SI coherent derived units with special names and symbols, e.g., Pa s for dynamic viscosity, N m for the moment of force, rad/s for angular acceleration, W/m^2 for heat flux density or irradiance, J/(kg K) for specific heat capacity, J/m^3 for energy density, J/mol for molar energy, J/(mol K) for molar entropy or molar heat capacity, Gy/s for absorbed dose rate, kat/m^3 for catalytic activity concentration.

Measurement units of quantities with the same dimension may be designated by the same name and symbol even when they are not of the same kind. The measurement unit of quantities of dimension number is the number one, symbol 1. In some cases, they are expressed by quotients such as millimole per mole, equal to 10^{-3}, and microgram per kilogram, equal to 10^{-9}.

Table 4. Units used with SI.

Quantity	Unit		
	Name	**Symbol**	**Definition**
time	minute hour day	min h d	1 min = 60 s 1 h = 60 min = 3600 s 1 d = 24 h = 86 400 s
length	astronomical unit	au	1 au = 149 597 870 700 m
plane and phase angle	degree minute second	$^\circ$ $'$ $''$	$1^\circ = (\pi/180)$ rad $1' = (1/60)^\circ = (\pi/10\,800)$ rad $1'' = (1/60)' = (\pi/648\,000)$ rad
area	hectare	ha	1 ha = 1 hm^2 = 10^4 m^2
volume	litre	l, L	1 l = 1 dm^3 = 10^{-3} m^3
mass	tonne dalton	t Da	1 t = 1 000 kg = 10^{-3} kg 1 Da = 1.660 539 066(50) $\times$ 10^{-27} kg
energy	electronnvolt	eV	1 eV = 1.602 176 634 $\times$ 10^{-19} J
level	neper bel	Np B	1 Np = ln e = 1 1 B = (1/2) ln 10 Np $\approx$ 1.1151293 Np

"Compound units", formed by multiplication of two or more units shall be printed in one of the two forms: N m or N · m, kW h, or kW · h. "Compound units" formed by dividing one unit by another one can be written in one of the following ways: $\frac{m}{s}$, m/s, m s^{-1}, m · s^{-1}. Exponentiation has priority over multiplication and division. A solidus (/) shall not be followed by a multiplication sign or a division sign on the same line unless parentheses are inserted to avoid any ambiguity, e.g., J/ (mol K).

3.3. *SI Prefixes*

In order to avoid large or small numerical values, decimal multiples and submultiples of the coherent SI units are formed with the SI prefixes listed in Table 5. These SI multiple units and SI submultiple units are not coherent with respect to ISQ.

Table 5. SI prefixes.

Factor	Prefix		Factor	Prefix	
	Name	**Symbol**		**Name**	**Symbol**
10^1	deca	da	10^{-1}	deci	d
10^2	hecto	h	10^{-2}	centi	c
10^3	kilo	k	10^{-3}	milli	m
10^6	mega	M	10^{-6}	micro	µ
10^9	giga	G	10^{-9}	nano	n
10^{12}	tera	T	10^{-12}	pico	p
10^{15}	peta	P	10^{-15}	femto	f
10^{18}	exa	E	10^{-18}	atto	a
10^{21}	zetta	Z	10^{-21}	zepto	z
10^{24}	yotta	Y	10^{-24}	yocto	y

The symbol of a prefix shall be combined with the single unit symbol to which it is directly attached, without a space between the symbol for the prefix and the symbol for the unit, forming a new symbol for a decimal multiple or submultiple. They can be raised to a positive or negative power or be combined with other unit symbols to form symbols for compound units, e.g., 1 $cm^3 = (10^{-2}\ m)^3 = 10^{-6}\ m^3$.

Compound prefixes shall not be used, e.g., write nm (nanometre) for 10^{-9} m, not mμm. For historical reasons, the name of the base unit of mass, the kilogram, contains the SI prefix "kilo". The names of its multiples are formed by adding the prefixes to the gram with the symbol g, e.g., milligram, symbol mg instead of microkilogram (μkg). The SI prefixes shall not be used to denote binary multiples, e.g., 1 kbit = 1 000 bit, but 1 Kibit = 1 024 bit (other prefixes for binary multiples are presented in ISO 80000-1, p. 8).

The SI prefixes are also used together with the ISO currency codes, e.g., 1 kEUR = 1 000 European euros (€); 1 MUSD = 10^6 US dollars ($), 1 GSEK = 10^9 Swedish crowns.

The unit one, symbol 1 is generally not written out explicitly when such a quantity is expressed numerically, e.g., the number of turns in a winding $N = 25 \times 1 = 25$. In the case of certain quantities, the unit one has a special name and symbol, e.g., plane angle $\alpha = 0.52$ rad = 0.52; level of power quantity $L_F = 12$ Np = 12. Such special names and symbols may be used in expressions for derived units, e.g., angular velocity $\omega = 17$ rad/s; attenuation coefficient $\alpha = 0.83$ Np/m.

Often per cent, symbol %, or per mil, symbol ‰, are used as a submultiple of the unit one. They are not quantities, therefore the "percentage" as a quantity name is not allowed. Additional information, such as % (m/m) or % (V/V) shall not be attached to the unit symbol %. The preferred way of expressing, e.g., the mass fraction of B, is $w_B = 78\%$. Abbreviations such as ppm, ppb, and ppt are ambiguous and shall not be used; instead of them, alternative mass or volume or amount of substance fractions can be expressed in units such as μg/g = 10^{-6}, ml/$m^3 = 10^{-9}$, or pmol/mol = 10^{-12}.

3.4. Frequent Mistakes and Some Recommendations

Some of the most often observed mistakes and recommendations regarding units are:

- When using an Arabic symbol for a number, the symbol of a unit shall be used, not the spelt-out name, e.g., 20% (not 20 per cent), 15 min (not 15 min). Spelt out numbers and names (e.g., fifteen minutes) are not familiar in science and engineering.
- The unit symbol rpm is not an SI unit symbol for rotational frequency (its symbol is n)—use min^{-1};
- The symbol for the unit degree Celsius is °C (Insert/Symbol/°), do not use the superscript 0, °C, or superscript o, °C;
- The symbol for the unit year is a, e.g., kt/a, not kt/yr or kt per year;
- A submultiple of 10^{-6} metre is micrometre, symbol μm, not micron;
- The SI multiple of the unit for mass can be kt (1000 kg), or Gg (10^9 g) but not million kg, Mkg;
- The SI unit for volume fraction is mL/m^3 or μL/L (not ppm), μL/m^3 or nL/L (not ppb);
- The SI unit for amount fraction is μmol/mol (not ppm), and nmol/mol (not ppb);
- The SI unit of concentration is mol/L or its submultiple mmol/L (not milli-equivalent).

4. Quantity Values and Numbers

4.1. Quantity Values

To express values of physical quantities, Arabic numerals followed by the international symbol for the unit shall be used, e.g., the wavelength of one of the sodium spectral lines is $\lambda = 5.896 \times 10^{-7}$ m = 589.6 nm. If the point is used as the decimal sign, the cross and not the half-high dot shall be used as the multiplication sign between two numbers. If the comma is used as the decimal sign, as practised by the ISO standards [14], both the cross and the half-high dot may be used as the multiplication sign between numbers. In some cases multiplication signs may be omitted, e.g., $4c - 5d$, $6ab$, $7(a + b)$, 3 ln 2.

The symbol for the unit shall be placed after the numerical value in the expression for a quantity, with a thin space between them, e.g., 12 m, 45 kg, 20 °C. This rule applies also to the units per cent, %, and per mil, ‰, e.g., 78%. The only exception to this rule applies for the units degree, minute, and second for plane angle where there is no space between the numerical value and the unit symbol, e.g., 90°, 50′, 32″.

If the quantity is expressed as a sum or a difference of quantities, then either parenthesis shall be used to combine numerical values, placing the common unit symbol after the complete numerical value, e.g., l = (12 – 7) m, or the expression shall be written as the sum or difference of expressions for quantities, e.g., l = 12 m – 7 m, but not l = 12 – 7 m; t = 23.6 °C, not t = 23.6 °C.

There shall be a thin space on both sides of a sign for dyadic operators such as mathematical signs –, <, ≤, =, >, ≥, +, –, ±, ×, e.g., a ≥ b, but not with monadic operators, e.g., +2.5, **–r**, ≥72. Other mathematical signs and symbols are given in ISO 80000-2.

Descriptive terms or names of quantities shall not be arranged in the form of a quantity names equation but rather expressed with the quantity symbols, e.g., density, $\rho = m/V$ where m is mass and V is volume, not density = mass/volume.

In expressing the value of a quantity as the product of a numerical value and a unit, both of them may be treated by ordinary rules of algebra. For example, the equation p = 48 kPa may equally be written p/kPa = 48. The quotient of a quantity and a unit shall be used in a column heading of a table so that the entries in the table are simply numbers. For example, a table of velocity squared versus pressure may be formatted as shown in Table 6.

Table 6. Expressing values of quantities using recommended column headings [1].

p/kPa	**$v^2/(m/s)^2$**
48.73	94 766
72.87	94 771
135.42	94 784

The axes of a graph may also be labelled in this way so that the tick marks are only numbers (Figure 1).

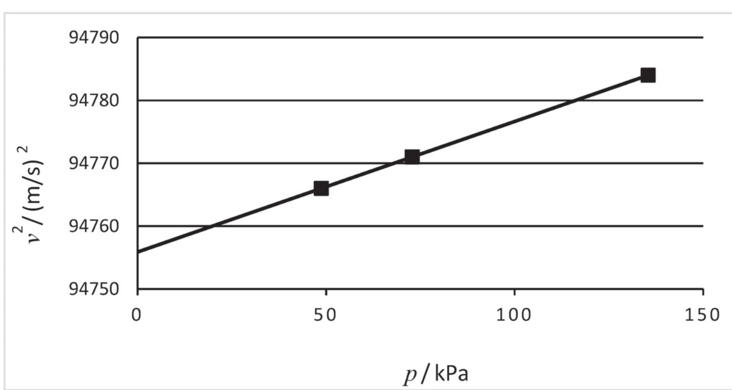

Figure 1. Labelling of axes in a graph [1].

4.2. Numbers

Numbers shall be printed in roman type, irrespective of the type used in the rest of the text. Numbers shall be ordered in groups of three digits, counting from the decimal sign towards the left and the right, and the groups shall be separated by a small space and not by a point or a comma or by other means, e.g., 7 172.656 03. The separation into groups of three should not be used for ordinal numbers used as reference numbers, e.g., ISO 80000-1. The year shall always be written without a space, e.g., 2021. If the magnitude (absolute value) of the number is less than 1, the decimal sign shall be preceded by a zero, e.g., 0.657 89.

The sign for multiplication of numbers is a cross (×, not x) or a half-high dot (·). There shall be a thin space on both sides of the cross or the dot. They shall be used to indicate the multiplication of numbers and numerical values, e.g., $l = 2.5 \times 10^3$ m; A = 80 mm × 25 mm, also in vector products and Cartesian products. The half-high dot shall be used to indicate a scalar product of vectors and is preferred for the multiplication of letter symbols. If the point is used as a decimal sign, the cross and not the half-high dot shall be used as a multiplication sign between numbers, e.g., 4 711.32 × 0.351 2. Division of one number by another is indicated in one of the following ways: $\frac{1}{2}$, 1/2, $1\ 2^{-1}$, $1 \cdot 2^{-1}$.

Digits of a number are called significant digits if the corresponding number is considered to lie within the error limit of the last digit(s); e.g., the number 401 000 can have from three to six significant digits what is differentiated by writing from 401×10^3 to 401.000×10^3. A standard uncertainty can be expressed in terms of the least significant digits in parentheses, e.g., l = 23.478 2(32) has the numerical value 23.478 2 and the standard uncertainty 32. The mathematical format 23.478 2 ± 0.003 2 shall be avoided as it does not contain all values between 23.481 4 and 23.475 0. Engineering tolerances 23.478 2 ± 0.003 2 contain the (upper and lower) limits and also all the values between them, symmetrically dispersed around the numerical value 23.478 2.

The rounding of numbers is explained in Annex B of the ISO 80000-1 standard.

4.3. Chemical Elements and Nuclides

Symbols of chemical elements shall be printed in roman type. The initial letter is a capital and the following letter, if any, is a lower case one. The nucleon (mass) number of a nuclide is shown in the left superscript position, e.g., ^{14}N. The number of atoms of a nuclide in a molecule is shown in the right subscript position, e.g., $^{14}N_2$; the number of atoms is equal to 1, if it is not indicated, e.g., H_2O. The proton (atomic) number of a nuclide is shown in the left subscript position, e.g., $_{64}Gd$. The state of ionization and the state of electrical excitation are shown in the right superscript position, e.g., Na^+, $(PO_4)^{3-}$. The state of nuclear excitation is shown with the symbol * in the left superscript position, e.g., $^{127*}Xe$.

5. Some Other Frequent Mistakes

There are some mistakes in printing that most authors are not aware of. The most frequent one is the use of a hyphen instead of the dash or minus. There are two slightly different conventions for using a dash. The more modern one is to put white spaces at both ends of a dash, while the older style uses no white spaces at all. Using the first one—you simply print a hyphen with a space before and after it (–), and the computer turns it into a dash after you finish the next word and add a space after it. This dash is called an en-dash as it takes approximately the width of the letter "N" or "n" (–) while an em-dash takes approximately the same width as the letter "M" or "m" (–). In addition:

- A hyphen (-) shall not be used instead of minus (−), or dash (–) in cases like Cl^-, m^{-1}; pH = 6–9, $\gamma(Fe^{2+})$ = 3–4 mg/L, July 8–12.
- The dash (not the hyphen), used with number range has no spaces before and after it, e.g., 80–97%, 1.5–1.8 USD/m^3, pp. 23–29. Spaces before and after each of them change their meanings from number range to minus.
- A range of values can be expressed by units at both bounds, e.g., from 20 MW to 35 MW, or a dash must be used, 20–35 MW.

The references shall be printed after carefully reading the Journal's *Instructions for Authors*. Besides using the dash, not the hyphen with the above-mentioned number ranges of pages (the same is true for a number range of journal's volumes), the following is observed:

- Journal names should be abbreviated according to the List of Title Word Abbreviations, e.g., [15].
- The www-references have to contain the date of access—according to ISO 8601 standard the calendar date is represented by the form YYYY-MM-DD, e.g., 2021-02-08.
- Initials of author names shall be separated by a space, e.g., Akal Solmaz, S. K., etc.

In the tables, numbers shall be vertically aligned according to the decimal sign. Acronyms shall not be used either in the article title or its abstract. The abstract shall be written in a single paragraph, including one sentence about: (a) the background/context, (b) findings, (c) discussion, (d) conclusions. Underscore the scientific value added by your paper in your abstract. Use the third person singular, instead of the first person singular or plural. Further observations include:

- Differentiate I/we will and I/we shall (future time).
- Make sure the pages are numbered.
- Several of your sentences are not properly referenced. Please make sure you attribute or reference them.
- Please avoid reference overkill/run-on, i.e., do not use more than three references per sentence. If you need to use more, make sure you state the key relevant idea of each reference.
- Make sure your conclusions section underscores the scientific value added by your paper, and/or the applicability of your findings/results.
- Mark that there is no spacing between the announcing sentence before the bulleted lines and the first bulleted line.

6. Conclusions and Outlook

This paper presents a need to join the efforts of the International Organization for Standardization and spread out the International System of Quantities, ISQ. After adopting the Latin and Greek letters, Arabic numerals, and International System of Units (SI), it is time to accept the ISQ in science and engineering by using it in articles, papers, and books from all fields. The ISQ covers nearly 1 000 physical quantities and mathematical items that are most frequently used in schools, in research and development, in industry and professional associations. The hesitation of many authors, scientists, and engineers as well as many scientific and professional journal editors to decide to use it is difficult to understand. How to explain to a pupil or a student that the same quantity has two or three different names, often even more symbols and units, preventing them to easily understand the connection of terms used in schools at different courses, e.g., physics, chemistry, electrical or mechanical engineering. What a loss of time and effort, synergy, and understanding!

The great disadvantage of ISO 80000 is that in contrast to the SI Brochure [1] it is not available in open access. Only some small parts of the standard can be reached on the Internet. Even of the general one, ISO 80000-1, only 12 pages out of 45 are open to the public. The member states of ISO and IEC shall agree to open the standards to all the interested in order to enable its wide usage. The costs for it are negligible in comparison to the potential public benefit. This is true also for national translations of the ISO 80000 standard series.

The present ISO 80000 part covers physics, physical chemistry, mechanical, electrical, and nuclear engineering. ISQ shall be extended to other fields of science and engineering. Life sciences (biology, ecology, medicine, etc.) are not covered so far although their importance is increasing. Chemical and process engineering and technology which covers chemicals and pharmaceuticals production, fuels extraction and refining, food and beverages value chain, production of materials (metals and alloys, ceramics and glass, pulp, paper and cardboard, cement and lime, plastics, leather, textiles and rubber, and corrosion protection) are not included in ISO 80000. ISO 80000-9 and the IUPAC Green Book [6] only cover physical chemistry and molecular physics. Unit operations, physicochemical separation and reaction processes, process design, optimization, and control as well as sustainable development urgently need standards of quantities, symbols, and units.

Multidisciplinary environmental engineering is of the utmost importance for biodiversity existence and for the sustainable development of the human race on Earth—it covers climate change, resource reduction, and efficiency, waste minimization towards zero waste, water, air and soil pollution, cleaning and reuse, energy and waste management with recycling, life cycle assessment, and circular economy, critical raw materials, dangerous substances, and human health. The need for ISO 80000 extension is urgent for civil engineering, too.

Social aspects with population growth and ageing, health and safety, social responsibility, quality management, and responsible care are also very important but the most urgent field is economics which is important during the process and product design, optimization, operations research, production, and evaluation of business results. The problem of applying economics is that there is no international standard available, the literature uses different definitions of terms, and acronyms are used instead of symbols for quantities.

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standards

Article

The Need to Accurately Define and Measure the Properties of Particles

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Abstract: When dealing with powders, a fundamental knowledge of their physical parameters is indispensable, with different methods and approaches proposed in literature. Results obtained differ widely and it is important to define standards to be applied, both toward the methods of investigation and the interpretation of experimental results. The present research intends to propose such standards, while defining general rules to be respected. Firstly, the problem of defining the particle size is inspected. It was found that describing the size of a particle is not as straightforward as one might suspect. Factors of non-sphericity and size distributions make it impossible to put 'size' in just one number. Whereas sieving can be used for coarser particles of a size in excess of about 50 µm, instrumental techniques span a wide size range. For fine particles, the occurrence of cohesive forces needs to be overcome and solvents, dispersants and sample mixing need to be applied. Secondly, the shape of the particles is examined. By defining sphericity, irregularly shaped particles are described. Finally, the density of particles, of particle assemblies and their voidage (volume fraction of voids) and the different ways to investigate them are explored.

Keywords: particles; size; size distribution; density; bed voidage

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1. Introduction

The design of fluid–solid processes often relies on using empirical correlations that include characteristic powder properties such as the particle size and its size spread, the particle shape and density and the bed voidage for particle assemblies [1–7]. Unfortunately, most correlations do only provide predictions within a range of ±25%. The reasons for this inaccuracy are not due to the lack of engineering skills, but in the complexity of unambiguously defining and measuring even these fundamental particle parameters. As a first guideline, ISO standards can be consulted. A first set of documents indeed provides guidance on instrument qualification and particle size and its size distribution measurements, whereas a second set deals with the representation of the results of the particle size analysis. These standards are periodically reviewed and confirmed. Within the first set of standards, we refer to the measurement techniques by gravitational methods [8], by laser diffraction method [9] and by sieving analysis [10], among others. The second set includes several parts of the ISO 9276 standard that specifically deal with the representation of results of particle size analysis in Part 2 [11] and with the descriptive and quantitative representation of particle shape and morphology in Part 6 [12]. Whereas in Part 2 particle shape factors are not taken into account, Part 6 recognizes the ineffectiveness of averaging the shape over all particles and restricts the methods to those that can be correlated with physical properties in industrial applications. Although particle shape and morphology are normally three-dimensional problems, Part 6 provides most definitions for two-dimensions considered a valid approach in using image analysis methods.

Since it is clear that numerous parameters affect the behavior of particles in different applications, it is utterly important to apply the most appropriate measurement and assessment methods for a specific application. This paper will hence review and discuss the size, shape, density and voidage determination and interpretation, while providing necessary recommendations.

2. Particle Size and Its Size Distribution (PSD)

2.1. The Average Particle Size

The determination of the particle size is often the first step in characterizing the particle. For perfect spherical particles, a valid definition of their size would be the diameter of the sphere. In industrial applications, however, perfect spherical particles are seldom encountered. There is no universal definition for particle size when dealing with non-spherical particles. A whole set of definitions is available, each appropriate in specific applications. The most commonly used definitions are listed in Table 1. Additional definitions, such as free-falling diameter, perimeter diameter, Feret's and Martin's diameter are seldom used. In view of the growing importance of studying ultrafine airborne particles or drug-delivering aerosols, among others, the aerodynamic and mobility particle diameters are frequently used. The former one is defined as the diameter of a sphere of density 1000 kg/m^3 (e.g., the density of water) which settles in still air at the same velocity as the particle in question [13–15]. The latter classifies charged particles according to their mobility in an electric field, followed by a particle counter to count particles of a specific mobility [16].

Table 1. Definitions of the particle diameter (adapted from [17]).

Symbol	Diameter Definition	Equivalent Sphere Diameters
d_A	Sieve	Largest sphere diameter that can pass through the square aperture of the sieve.
d_v	Volume	Sphere diameter when particle and sphere volumes are equal.
d_s	Surface	Sphere diameter when particle and sphere surfaces are equal.
d_{SV}	Surface to Volume	Sphere diameter when the surface area to volume ratio of the sphere and the particle are equal.

2.2. The Particle Size Distribution

As stated before, the particles of a powder seldom have a uniform size, but are instead characterized by a whole range of particle sizes, representing a size distribution. The knowledge of this size distribution is often of great importance for evaluating powders, for instance, in milled powders where the particle size should not exceed a certain threshold size as determined by quality constraints.

To deal with this problem, the distribution density, $f(d)$, and the cumulative fraction, $F(d)$, are defined. They can be based on the number of particles, although linear (length), square (surface area) or three-dimensional (volume or mass) based distributions are also used. These density functions are indicated by $f_N(d)$ and $F_N(d)$ for the distribution by numbers; $f_L(d)$ and $F_L(d)$ for the distribution by length; $f_s(d)$ and $F_S(d)$ for the distribution by surface area; and $f_M(d)$ and $F_M(d)$ for a mass distribution. In these definitions, d is the relevant particle size (see Table 1). The distribution by length is seldom used in practice, but is given for reasons of completeness.

For the four possible distribution variants, the distribution density is used to predict the chance that a specific particle size will fall within a certain size interval $d \in \{a, b\}$:

$$P[a \leq d \leq b] = \int_a^b f(d)\mathrm{d}d, \tag{1}$$

Or more general: $f(d)\mathrm{d}d$ is the probability of d falling within the infinitesimal interval [d, d + dd].

The cumulative fraction is defined as follows:

$$\mathrm{F}(d) = \int_{-\infty}^{d} f(d)\mathrm{d}d, \tag{2}$$

Since the cumulative fraction integrates the distribution density, the latter can be calculated by taking the derivative of the former.

$$f(d) = \frac{\mathrm{dF}(d)}{\mathrm{d}d}, \tag{3}$$

In most cases, the size distribution is obtained by experiments that yield a discrete approximation of the distribution. In this approximation, the continuous distribution density, $f(d)$, is divided into I parts $i = \{1, \ldots, i\}$, each with a range of sizes of Δd_i, an average size d_i and a value of the distribution $f(d_i)$. In Equations (4)–(7), the definitions of the discrete distribution densities and the cumulative fraction are given with j as the index of the j-th part of the discrete distribution that corresponds with the value of d_i:

$$f_\mathrm{N}(d_i) = \frac{n_i}{N\Delta d_i}, \text{ and } \mathrm{F_N}(d) = \int_0^d f_\mathrm{N}(d)\mathrm{d}d \cong \sum_i^j f_\mathrm{N}(d_i)\Delta d_i \tag{4}$$

$$f_\mathrm{L}(d_i) = \frac{l_i}{L\Delta d_i}, \text{ and } \mathrm{F_L}(d) = \int_0^d f_\mathrm{L}(d)\mathrm{d}d \cong \sum_i^j f_\mathrm{L}(d_i)\Delta d_i \tag{5}$$

$$f_\mathrm{S}(d_i) = \frac{s_i}{S\Delta d_i}, \text{ and } \mathrm{F_S}(d) = \int_0^d f_\mathrm{S}(d)\mathrm{d}d \cong \sum_i^j f_\mathrm{S}(d_i)\Delta d_i \tag{6}$$

$$f_\mathrm{M}(d_i) = \frac{m_i}{M\Delta d_i}, \text{ and } \mathrm{F_M}(d) = \int_0^d f_\mathrm{M}(d)\mathrm{d}d \cong \sum_i^j f_\mathrm{M}(d_i)\Delta d_i \tag{7}$$

with n_i, l_i, s_i, m_i being the number, length, surface and mass in a size range i and N, L, S and M the total number, length surface and mass.

The different types of distributions are related to each other, by introducing appropriate geometrics shape factors k_1, k_2 and k_3:

$$f_\mathrm{L}(d) = k_1 d\, f_\mathrm{N}(d) \tag{8}$$

$$f_\mathrm{S}(d) = k_2 d^{\,2} f_\mathrm{N}(d) \tag{9}$$

$$f_\mathrm{M}(d) = k_3 d^{\,3} f_\mathrm{N}(d) \tag{10}$$

The cumulative distributions are also related to each other and can be based on a continuous frequency distribution or on a discrete approximation:

$$\mathrm{F_L}(d) = \int_0^d k_1 d f_\mathrm{N}(d)\mathrm{d}d = \int_0^d k_1 d\mathrm{dF_N} \cong \sum_i^j k_1 d_i f_\mathrm{N}(d_i)\Delta d_i \tag{11}$$

$$\mathrm{F_S}(d) = \int_0^d k_2 d^{\,2} f_\mathrm{N}(d)\mathrm{d}d = \int_0^d k_2 d^2\mathrm{dF_N} \cong \sum_i^j k_2 d_i^{\,2} f_\mathrm{N}(d_i)\Delta d_i \tag{12}$$

$$\mathrm{F_M}(d) = \int_0^d k_3 d^{\,3} f_\mathrm{N}(d)\mathrm{d}d = \int_0^d k_3 d^{\,3}\mathrm{dF_N} \cong \sum_i^j k_3 d_i^{\,3} f_\mathrm{N}(d_i)\Delta d_i \tag{13}$$

If the discrete distribution is known, the shape factors can be determined as illustrated below:

$$f_S \Delta d_i = \frac{n_i s_i}{\sum_i^I n_i s_i} = \frac{N \Delta d_i f_N(d_i) s_i}{\sum_i^I N \Delta d_i f_N(d_i) s_i} = \frac{f_N(d_i) s_i}{\sum_i^I f_N(d_i) s_i} \quad (14)$$

Let $s_i = \pi d_i^2$ and combined with Equation (3) the shape factor k_2 is the following:

$$k_2 = \frac{1}{\sum d_i^2 f_N(d_i) \Delta d_i} \quad (15)$$

The other shape factors are derived in a similar way:

$$k_1 = \frac{1}{\sum d_i f_N(d_i) \Delta d_i} \quad (16)$$

$$k_3 = \frac{1}{\sum d_i^3 f_N(d_i) \Delta d_i} \quad (17)$$

The significance of using the correct base (length, area or volume) will be clarified in the following example for a sieve analysis of a powder with data shown in Table 2.

Table 2. Results of a sieve analysis for particles with absolute density of 2 600 kg/m^3.

Sieve Size (mm)	Average Size (mm)	Sieve Mass (g)	Mass Fraction
0.04–0.06	0.05	0.1	0.03
0.06–0.10	0.08	0.4	0.11
0.010–0.18	0.14	0.7	0.19
0.18–0.30	0.24	0.9	0.25
0.30–0.42	0.36	0.7	0.19
0.42–0.59	0.5	0.5	0.14
0.59–0.83	0.71	0.2	0.06
0.83–1.00	0.92	0.1	0.03
Total		3.6	1

The volume occupied by the particles is obtained as the ratio of the sieve mass and the absolute density of the particle. The number of particles, n, is obtained by dividing the volume by the volume of one particle, $\frac{\pi}{6} d^3$ with d as the sieve size opening. Additionally, the total particle surface area for a given size is obtained by $n\pi d^2$. The results are shown in Figure 1.

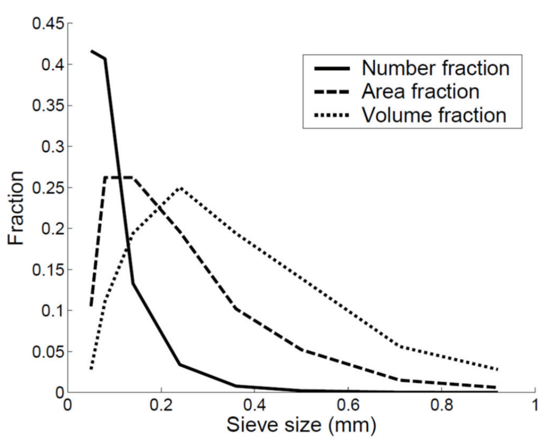

Figure 1. Number, area and volume fractions.

Figure 2 shows that the number and surface area distributions are significantly affected by the smaller particles being present. This is expected, since a small mass of fines contains a large number of particles with a high surface area.

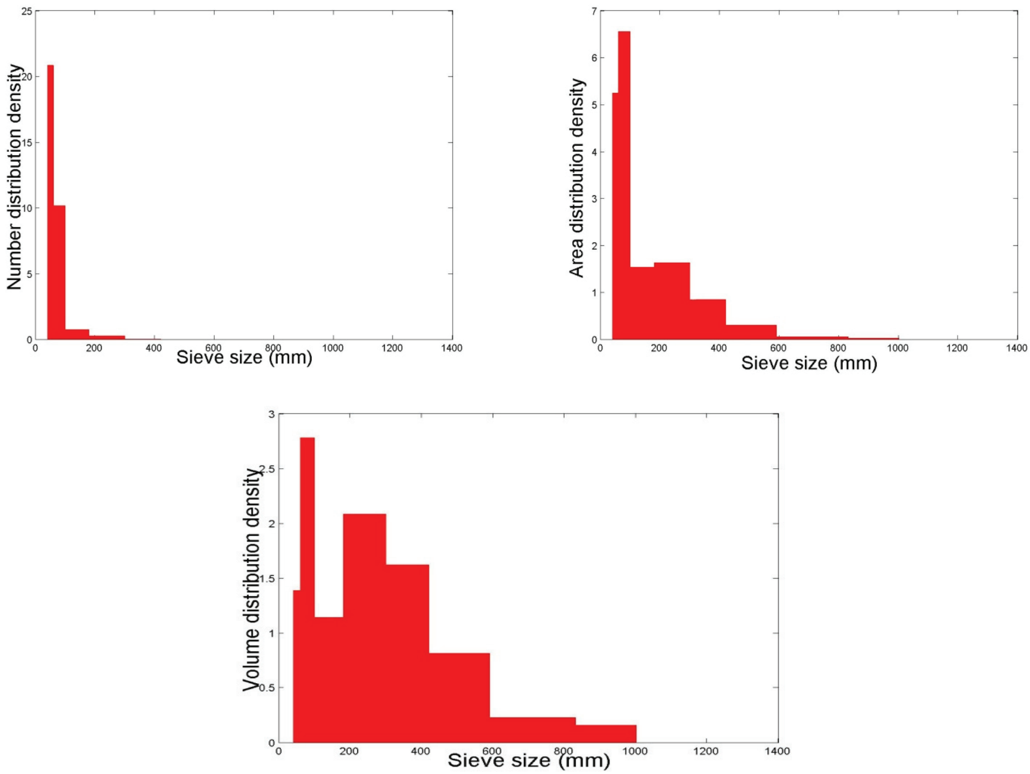

Figure 2. Number, area and volume size distributions.

The distribution results can be fitted to a function. A popular fitting equation is the two-parameter log-normal function [18]. Its positive skew describes the commonly encountered phenomenon that more fine particles are measured than larger ones as illustrated in Figure 2.

The log-normal distribution and its cumulative counterpart are given in Equations (18) and (19):

$$f(d, \mu, \sigma) = \frac{1}{d\sigma\sqrt{2\pi}} \exp\left(-\frac{\ln(d-\mu)^2}{2\sigma}\right) \tag{18}$$

$$\mathrm{F}(d, \mu, \sigma) = \frac{1}{2} + \frac{1}{2}\mathrm{erf}\left(\frac{\ln d - \mu}{\sqrt{2\sigma^2}}\right) \tag{19}$$

with μ and σ as the mean and standard deviations of the natural logarithm of the particle size and erf as the error function.

The log-normal distribution function is illustrated in Figures 3 and 4 for different values of μ and σ.

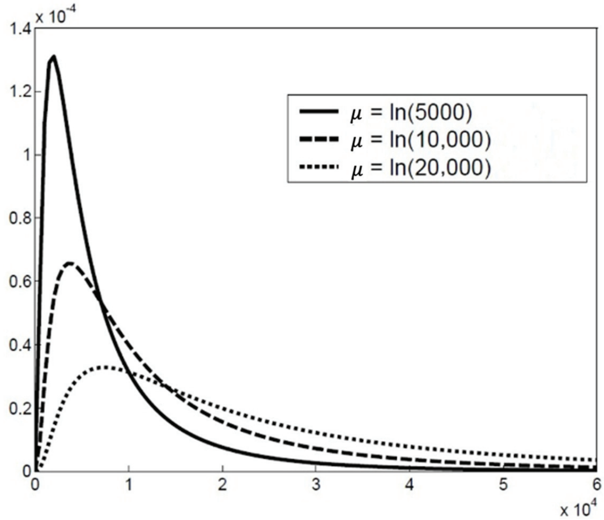

Figure 3. Log-normal distribution for different values of μ and σ = 1.0.

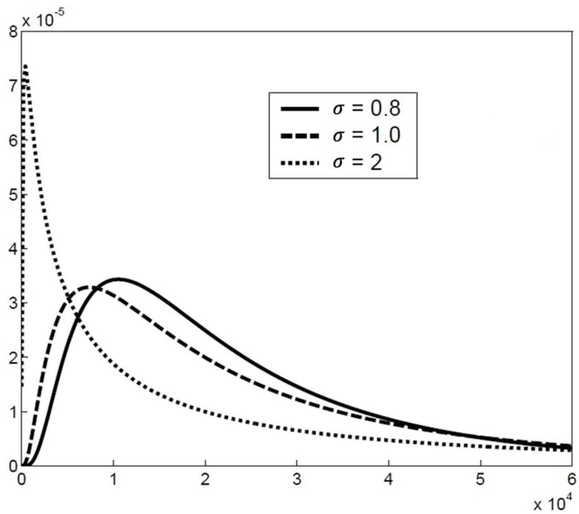

Figure 4. Log-normal distribution for different values of σ, for a constant μ = ln(20 000).

The distribution function is often written in the form of Equation (20), developed by Svarovsky [18]. In this form, the mode d_m (the size with maximum distribution density) is used as a parameter instead of the mean.

$$\mathrm{F}(d, d_\mathrm{m}, \sigma) = a \exp\left(-b \ln^2\left(\frac{d}{d_\mathrm{m}}\right)\right) \tag{20}$$

with

$$a = \frac{1}{d_\mathrm{m}} \sqrt{\frac{b}{\pi} \exp\left(\frac{-1}{4b}\right)},\ b = \frac{1}{2 \ln^2(\sigma)}$$

Instead of trying to fit the distribution data, it is also possible to summarize them in some key numbers such as the mean, modus, median and spread.

Because of this wide variety of definitions, the calculation of the mean can be somewhat confusing. In general, the calculation of the mean is defined as in Equation (21).

$$g\left(\overline{d}\right) = \int_0^{\infty} g(d)f(d)\mathrm{d}d \cong \sum_i^I g(d_i)f(d_i)\Delta d_i \quad (21)$$

with d_i as the average size in an increment range of size Δd_i.

Depending on the application, different functions of g(d) are used, as listed in Table 3.

Table 3. Different means and distribution functions.

Mean	g(*d*)	Formula
Arithmetic	d	$\overline{d}_\mathrm{a} = \sum_i^{\infty} d_i f(d_i)\Delta d_i$
Quadratic	d^2	$\overline{d}_\mathrm{q} = \sqrt{\sum_i^{\infty} d_i^2 f(d_i)\Delta d_i}$
Cubic	d^3	$\overline{d}_\mathrm{c} = \sqrt[3]{\sum_i^{\infty} d_i^3 f(d_i)\Delta d_i}$
Geometric	Log(d)	$\overline{d}_\mathrm{g} = 10^{\sum_i^{\infty} \log(d_i)f(d_i)\Delta d_i}$
Harmonic	d^{-1}	$\overline{d}_\mathrm{h} = \left(\sum_i^{\infty} d_i^{-1} f(d_i)\Delta d_i\right)^{-1}$

Other indicators of the average particle size in a powder are the modus and mean. The modus (d_m) is, as already stated, the most commonly found size in the distribution. As opposed to the mean and the modus, the median ($d_{50\%}$) is most easily identified using the cumulative fraction, F(d), where it corresponds to the 50 %-value.

An indication of the size distribution is given by the spread, σ, and the relative spread, $\sigma/d_{50\%,}$ with the following definitions:

$$\sigma = \frac{d_{84\%} - d_{16\%}}{2} \quad (22)$$

$$\frac{\sigma}{d_{50\%}} = \frac{d_{84\%} - d_{16\%}}{2d_{50\%}} \quad (23)$$

In Equations (22) and (23), $d_{84\%}$ and $d_{16\%}$ correspond with the particle size with a cumulative fraction F(d) equal to 84 % and 16 %, respectively. Some particle size analyzers (e.g., laser diffraction) use a slightly different definition with the spread evaluated between $d_{90\%}$ and $d_{10\%}$.

The mean, median, modus and spread are illustrated by a sieving test. A sand mixture was sieved and analyzed with the results presented in Table 4.

Table 4. Size distribution of a sieved sand.

Sieve Aperture (µm)	Size d_A (µm)	Weight% in Range Δd_i
600–500	550	0.5
500–420	460	11.6
420–350	385	11.25
350–300	325	14.45
300–250	275	20.8
250–210	230	13.85
210–180	195	12.5
180–150	165	11.9
150–125	137	3.15

Based on this data, using Equation (7), the distribution and cumulative fraction was calculated. The results from these calculations are presented in Figures 5 and 6. Additionally, the different kinds of means, the median, the modus and the spread were calculated. Note that the size range Δdi is not uniform.

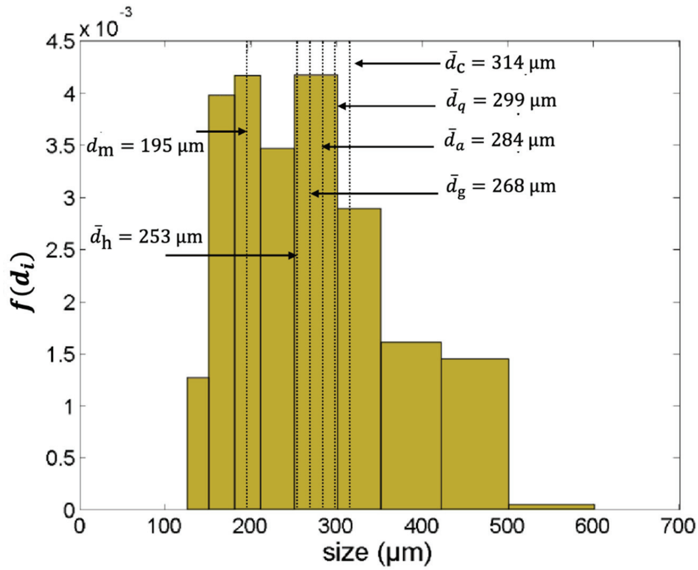

Figure 5. Distribution $f(d_i)$ of the sieved sand with indications of the different mean values, with the modus, d_m; and $\overline{d_a}$, $\overline{d_q}$, $\overline{d_c}$, $\overline{d_h}$, $\overline{d_g}$ as arithmetic, quadratic, cubic, harmonic and geometric means.

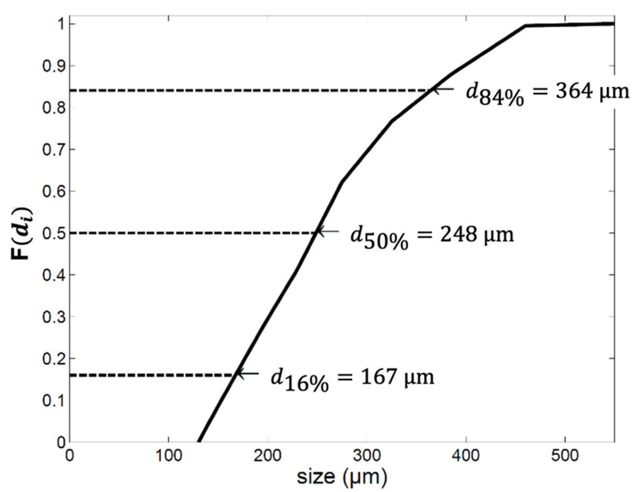

Figure 6. Cumulative fraction with indications of the median $d_{50\%}$ and the fractions $d_{16\%}$ and $d_{84\%}$. The spread σ is 197 µm while the relative spread $\sigma / d_{50\%}$ equals 0.79.

2.3. Particle Size and Size Distribution Measurements

2.3.1. Common Instrumental Techniques

Different methods of measurement can be used, as depicted in Figure 7 [19–23].

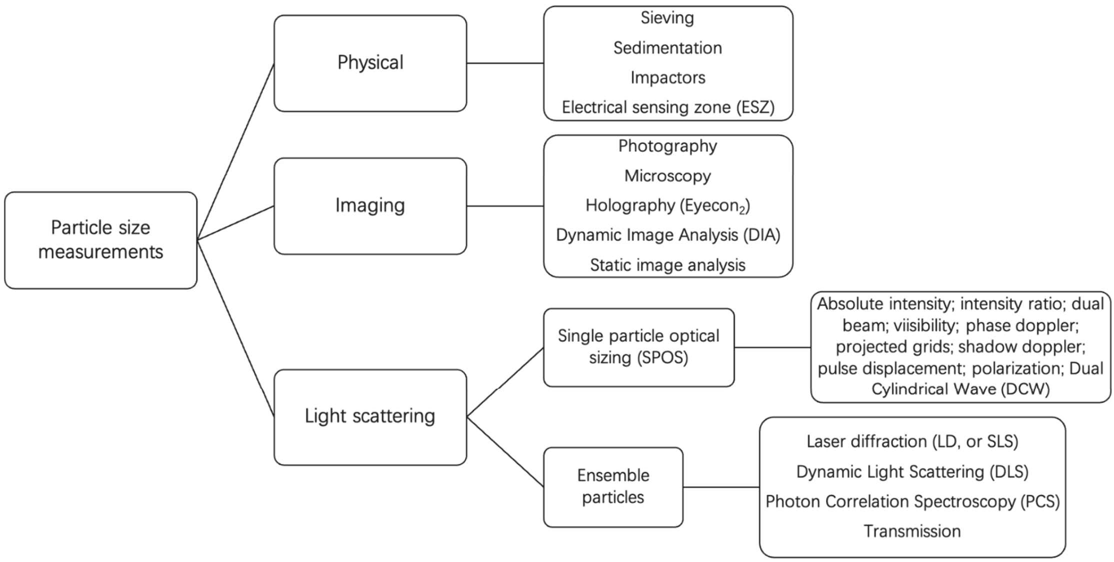

Figure 7. Particle size distribution measurements.

Each method covers a characteristic size range within which measurement is possible. These ranges partly overlap, as is shown in Figure 8. However, the results for measuring the same sample vary considerably. In some of the techniques, except imaging-based ones, the PSD is affected by the random orientation of particles during measurements. In principle, image analysis is preferred to provide physically relevant particle sizes of well-dispersed, irregularly shaped particles.

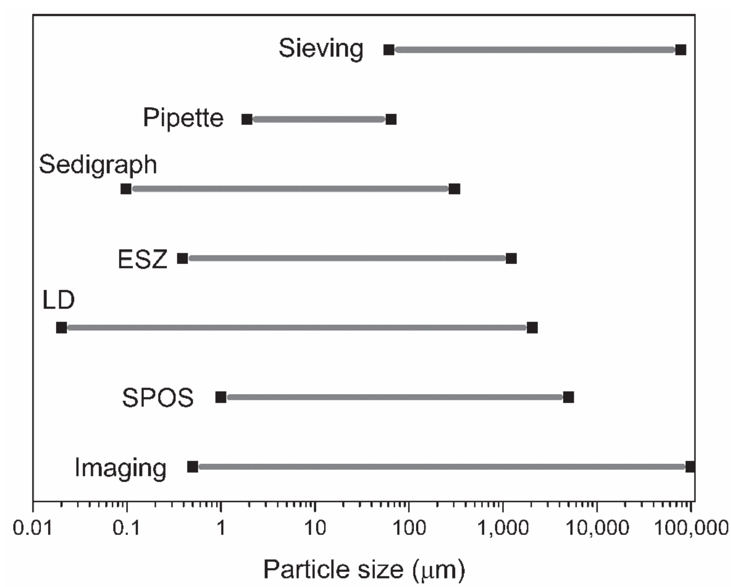

Figure 8. Measuring ranges of the various techniques, with acronyms of Figure 7 (adapted from [24]).

Each method provides different sizes and PSD types, as illustrated in Table 5.

Table 5. Instrumental of particle size measurements.

Method	Approx. Size (μm)	Size Type	Basis of the Size Distribution
Sieving (wet/dry) Woven mesh Electro-formed mesh	25–4000 5–120	d_A	Mass
Microscopy Optical Electron	0.8–150 0.001–5	d_z, d_F, d_M d_{SH}, d_{CH}	Number
Gravity sedimentation	2–100	d_{St}, d_f	Mass
Centrifugal sedimentation	0.01–10	d_{St}, d_f	Mass
Elutriation (dry)	5–100	d_{St}, d_f	Mass
Centrifugal elutriation (dry)	2–50		Mass
Impactors (dry)	0.3–50		Mass or number
Coulter Counter (electrical resistance)	0.8–200	d_v	Number
Fraunhofer diffraction (laser)	1–2000	Specific diameter	Volume
Mie light scattering (laser)	0.1–40	Specific diameter	Volume
Photon correlation spectroscopy	0.003–3	Specific diameter	Number
Doppler phase shift (laser)	$1–10^4$	Specific diameter	Mean only

2.3.2. Parameters Affecting the Instrumental Particle Size Measurement

Although the particle size analysis is expected to accurately measure the particle size distribution in any size range, repeat measurements often differ. It is imperative to respect rules regarding the sample preparation, the measurement procedure and the analyzers themselves. Standard methods should hence be used. Instrument specifications should be accounted for and the results' presentation should be standardized. Various ISO standards were already referred to in the introduction of the paper. An extensive research of Zhang et al. [25] investigated the major parameters to be considered. The main conclusions of the study are highlighted below and consider parameters of Table 6.

Table 6. Parameters affecting the instrumental particle size measurement (adapted from [25]).

	Parameters
Powder sample	Particle density, particle refractive index and weight of the sample
Solvent	Type, density, refractive index and viscosity
Dispersant	Organic/anorganic, concentration
Dispersion	Ultrasonication bath or tip (position, size, material), suspension volume, power, frequency and ultrasonication duration

Although demi-water is mostly used for insoluble materials, its pH needs to be pH-adapted to be in line with the zeta-potential of the particles. Denser insoluble particles will need to use organic liquids of appropriate density as solvents. Iso-propanol and aromatics are frequently used. Alcohols promote the de-agglomeration of particles. Acetone or aromatics tend to provoke particle adhesion on the cell wall, thus hampering measurement reproducibility. Normally, a 25 vol% of iso-propanol is selected.

Different particles and different solvents call for different dispersants. Polyphosphates are commonly applied for insoluble materials, with hexa-metaphosphate as the most effective, although it loses its activity within 24 h. The type of dispersant and its concentration should reduce the zeta-potential, preferably to below −60 mV, and should avoid obscuration and sedimentation. Normally, a concentration of 100 ppm would lower the zeta-potential to below ~60 mV. An over-dosage could however lead to particle agglomeration rather than dispersion. Low-molecular-weight organic dispersants, such as Daxad 11G [26], are valid alternatives and can be applied at concentrations of about 1 wt%.

Beside using dispersants, particle samples should be mechanically de-agglomerated during the measurement by either ultrasonic or mechanical mixing. The mixing energy input should be limited to avoid particle attrition or disintegration. Both mechanical and ultrasonic mixing are provided in commercial equipment. The sonication output power is normally set at about 200 to 300 W, and the sonication duration has a limited effect only if exceeding 0.5 to 1 min.

The particle refractive index considerably affects the sizing results, although results for a refractive index in excess of 1.8 to 2 hardly affect the results. Particle refractive index values are listed in several handbooks such as [26].

The amount of sample is critical, with excess sample leading to agglomeration. A concentration of 2 g/L is recommended.

These findings and recommendations were confirmed by several researchers with respect to the medium of suspension and dispersant [27,28]. Vdovic et al. [29] investigated the effects of sample pre-treatment with dispersant. Storti and Balsamo [30] investigated the effect of dispersing methods for sands, whereas Schulte and Lehmkuhl [31] assessed the differences in results by the Mie and Fraunhofer theory. Yang et al. [32] found minor differences of PSD results between the laser diffraction sieve–pipette method.

Although each technique has its own basis (mass, number, volume) where it yields the most reliable data, results will be fairly comparable if presented on the same basis and scale in a logarithmic or normalized distribution, even for very wide PSD [33–35].

2.3.3. Comparing the Common Particle Size Analyzers

Some particle analyzers were tested for 2 powders, i.e., Al_2O_3 (3 130 kg/m^3) and SiC (3 960 kg/m^3), with additional properties given in Table 7 [25]. Ten measurements were carried out. The results and coefficients of variation are given in Table 8.

Table 7. Sample properties and optimum dispersants.

	SiC	**Al_2O_3**
refractive index (−)	2.65	1.76
dispersant and concentration (wt%)	tri-sodium phosphate 0.025	sodium hexametaphosphate 0.05
ζ-potential (mV)	−64	−97.5

Table 8. Comparison of results for Al_2O_3 and SiC, adapted from [25].

Al_2O_3	**X-ray Sedimentation**	**Photo-Sedimentation**	**Light Obscuration**	**Electrical Sensing Zone**	**Laser Diffraction**
d10 (µm)	(0.95)	(0.95)	1.16	1.16	0.71
CV (%)	2.80	14.20	5.80	8.30	35.9
d50 (µm)	1.81	1.69	2.88	2.16	2.10
CV (%)	3.00	12.60	7.20	4.80	12.70
d90 (µm)	3.68	4.13	4.89	4.07	4.69
CV (%)	5.20	41.80	3.20	4.60	9.60
SiC	**X-ray Sedimentation**	**Photo-Sedimentation**	**Light Obscuration**	**Electrical Sensing Zone**	**Laser Diffraction**
d10 (µm)	(0.11)	(0.16)	0.63	(0.20)	(0.24)
CV (%)	(15.20)	(27.20)	3.50	(21.30)	34.50
d50 (µm)	0.47	0.47	1.02	0.68	0.64
CV (%)	21.70	39.40	6.90	10.40	18.00
d90 (µm)	1.92	1.60	3.12	2.71	1.96
CV (%)	10.80	34.70	17.70	14.50	31.20

The coefficients of variation of d_{50} are generally less than 10%, except for photo-sedimentation with a ~20% relative accuracy.

3. Particle Shape

It was already clear from the multiple particle size definitions in the previous section that perfectly spherical particles are a curiosity. However, correctly quantifying the shape of particles in practice proves to be quite difficult. A commonly used concept is the sphericity, ψ $(-)$, of a particle.

$$\psi = \frac{\text{surface area of a sphere with the same volume as the particle}}{\text{surface area of the particle}} \tag{24}$$

It can be shown that

$$\psi = \frac{d_{\mathrm{sv}}}{d_{\mathrm{v}}} \tag{25}$$

For particles with regular shapes, the sphericity can theoretically be calculated from the geometry using Equation (25). Some correlations are given in Table 9.

Table 9. Sphericities for regular shapes ([36], pp. 5–54; [37], p. 928).

Shape	Relative Proportions	ψ
Spheroid	1 : 1 : 2	0.93
	1 : 2 : 2	0.92
	1 : 1 : 4	0.78
	1 : 4 : 4	0.70
	1 : 2 : 4	0.79
Cylinder	Height = 0.5 × diameter	0.83
	Height = 0.25 × diameter	0.69
Cube	-	0.81

For non-regularly shaped particles, both the volume diameter (d_{v}) and the surface to volume diameter (d_{sv}) have to be determined experimentally.

The volume diameter can be calculated with following formula:

$$d_{\mathrm{v}} = \left[\frac{6M}{\rho_{\mathrm{p}}\pi n}\right]^{1/3} \tag{26}$$

with M being the total mass (kg) and n the number of particles in the examined powder and ρ_{p}, the particle density (kg/m^3), which will be discussed in detail in the following section.

The surface-to-volume ratio can be determined with a pressure-drop experiment. In this experiment, the powder is put in a circular tube through which a gas is blown at low flow rates and the occurring pressure gradients are measured. For a low Reynolds, the Carman-Kozeny equation relates the measured pressure gradient to the bed voidage:

If

$$\mathrm{Re} = \frac{\rho_{\mathrm{g}} \nu d_{\mathrm{sv}}}{\mu} < 2 \tag{27}$$

Then

$$\frac{\Delta p}{L} = 150 \frac{(1-\varepsilon)^2}{\varepsilon^3} \frac{\mu \nu}{d_{\mathrm{sv}}^2} \tag{28}$$

with Δp being the pressure drop (Pa), L the bed depth (m), ε the bed voidage (-), μ the gas viscosity (Pa s) and ν the superficial velocity (m/s).

The sphericity of some common materials is listed in Table 10.

Table 10. Sphericity of some common materials.

Material	ψ
Crushed coal	0.75
Crushed sandstone	0.8–0.9
Sand (average)	0.75
Round sand	0.83
Flint sand, jagged	0.65
Crushed glass	0.65
Common salt	0.84
Most crushed materials	0.6–0.8

4. Particle Density and Bed Voidage

The knowledge of particle and bed density is in many applications a requisite with the obvious examples of fixed beds, fluidized beds and compaction processes.

The particle density, ρ_{P} (kg/m^3), bed bulk density, ρ_{B} (kg/m^3), density of the fluid occupying the intra- and interparticle empty space, ρ_{g}, and bed voidage, ε (−), are correlated by:

$$\rho_{\mathrm{B}} = \varepsilon\rho_{\mathrm{g}} + (1-\varepsilon)\rho_{\mathrm{P}} \text{ with } \rho_{\mathrm{g}} \approx 0,\ \varepsilon = 1 - \rho_{\mathrm{B}}/\rho_{\mathrm{P}} \tag{29}$$

The approximation that ρ_{g} is nearly zero is justified for a gas as fluid.

The particle density in Equation (29) should not be confused with the absolute or skeletal density, ρ_{abs} (kg/m^3), of the material out of which the particle is composed. Due to a possible internal porous structure of the particle, the particle density will often be lower than the absolute density. Sometimes the particle density is denoted with other names such as hydrodynamic, apparent, envelope, effective or piece density [38,39].

4.1. Particle Density

An accurate measuring of the particle density can be quite difficult, especially if the particle is highly porous, as illustrated in Figure 9. This is exemplified by the disrupting influence of humidity on measurements. In a humid atmosphere, water will adsorb in the porous with the amount of condensed liquid being a function of relative humidity, pore diameter and surface tension.

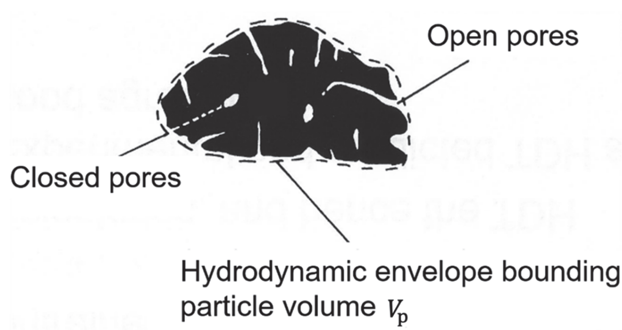

Figure 9. A porous particle.

In the case of porous particles, the particle density is a ratio of the mass to the hydrodynamic envelope bounding particle volume, $\rho_{\mathrm{P}} = M/V_{\mathrm{P}}$.

In general, 7 methods or measuring devices can be distinguished to determine the particle density: (i) caking end-point measurements, (ii) mercury porosimeters, (iii) comparative measurements, (iv) gas flow measurements, (v) powder displacement measurements, (vi) minimum fluidization velocity measurements and (vii) photographic measurements.

(1) Caking end-point measurements are sometimes performed in the petrochemical industry for rapid and cheap estimations of pore volume. In these measurements,

the investigated powder is put in a vibrating flask and a liquid with low viscosity or volatility (for example, water) is added incrementally. As long as the liquid is absorbed into the microscopic pores, the powder remains free-flowing. If the pores are completely filled, any surplus of liquid will coat the surface of the particles and cause the formation of liquid bridges, i.e., caking. This surplus depends on pore size and the surface tension. A complete filling-up of the pores is often impossible due to surface tension constraints. As a result, the caking end-point measurement method tends to overestimate the particle density. If the pore volume is determined, the particle density can be calculated with:

$$\rho_{\mathrm{p}} = \frac{1}{x + 1/\rho_{\mathrm{abs}}} \tag{30}$$

with x as the specific pore volume (m^3/kg).

The absolute density (ρ_{abs}) can be measured with a balance (absolute mass) and pycnometer (absolute volume).

(2) In a porosimeter, mercury under high pressure is forced into to the pores of the particles. Eventually, the pore size can be determined. As in the caking end-point method, the particle density is determined from Equation (30). A major setback of this measuring method is its high cost.
(3) The particle density can also be determined in the comparative method by examining the tapped bulk density, ρ_{BT}, of both the sample and a control powder. Then, applying Equation (31) yields the particle density of the investigated sample powder.

$$\rho_{\mathrm{pX}} = k \frac{\rho_{\mathrm{BTX}}}{\rho_{\mathrm{BTC}}} \rho_{\mathrm{pc}} \tag{31}$$

with ρ_{BTX} and ρ_{BTC} as the tapped bulk density of the sample and the control powder and ρ_{pC} and ρ_{pX} as the particle density of the sample and control powder. Since the control powder might have a different particle shape than that of the unknown powder, a shape factor k is introduced, with illustrative values as given below:

- $k = 1$ for identically shaped sample particles and control particles
- $k \approx 0.82$ for rounded or spherical sample particles and angular control particles
- $k \approx 1/0.82$ for angular sample particles and spherical or rounded control particles

(4) In the adapted gas flow technique of Ergun, the particle density is determined by comparing the pressure drop over a bed with minimum voidage to a bed with a maximum voidage. Maximum voidage can be achieved by fluidizing the sample and letting it gently settle. The resulting bed can next be tapped for a sufficient length of time to reach the state of minimal voidage. In both situations, the bed height L_{A} (aerated) and L_{T} (tapped) is measured. Additionally, the pressure drop, Δp, is recorded for at least four different gas velocities. Next, the pressure drop is plotted against the superficial velocity (v) and the slope within the laminar flow regime (Re < 2) is measured. With these values, the particle density can be calculated using a rearranged form of Equation (28), i.e., the Ergun equation in the laminar flow regime, with L, the bed length (m), ε the bed voidage (-) and μ the gas viscosity (Pa s).
(5) Rearranged, the slopes of the graphs S_{A} and S_{B} for the two beds are

$$S_{\mathrm{A}} = \left[\frac{\Delta p}{v}\right]_{\mathrm{T}} = \frac{150\mu}{d_{\mathrm{sv}}^2} L_{\mathrm{A}} \frac{(1-\varepsilon_{\mathrm{A}})^2}{\varepsilon_{\mathrm{A}}^3} \tag{32}$$

$$S_{\mathrm{T}} = \left[\frac{\Delta p}{v}\right]_{\mathrm{T}} = \frac{150\mu}{d_{\mathrm{sv}}^2} L_{\mathrm{T}} \frac{(1-\varepsilon_{\mathrm{T}})^2}{\varepsilon_{\mathrm{T}}^3} \tag{33}$$

$$\frac{L_{\mathrm{A}}}{L_{\mathrm{T}}} = \frac{\rho_{\mathrm{BT}}}{\rho_{\mathrm{BA}}} \tag{34}$$

$$1 - \varepsilon_A = \frac{\rho_{BA}}{\rho_P} \tag{35}$$

$$1 - \varepsilon_T = \frac{\rho_{BT}}{\rho_P} \tag{36}$$

Dividing Equation (32) by Equation (33) and substituting L_A, L_T, ε_A and ε_T, yields:

$$\frac{S_A}{S_T} = \frac{\rho_{BA}}{\rho_{BT}} \left(\frac{\rho_P - \rho_{BT}}{\rho_P - \rho_{BA}} \right)^3 \tag{37}$$

ρ_P can be calculated with:

$$Y = \frac{S_A}{S_T} \frac{\rho_{BT}}{\rho_{BA}} \tag{38}$$

$$\rho_P = \frac{\rho_{BT} - Y^{1/3} \rho_{BA}}{1 - Y^{1/3}} \tag{39}$$

Since the method requires an accurate measurement of the pressure drop, caution should be made when dealing with cohesive powders as channeling is likely to occur.

(6) In the powder displacement method, the particle density is measured by comparing the tapped bulk density of a control powder with a mixture of the control and the sample powder. This technique is specific because the fine powder is used as pycnometric fluid to fill the open pores in the investigated particles. As such, the pycnometric powder must be free-flowing, non-porous and sufficiently smaller than the sample particles. If the latter condition is not fulfilled, the comparison between the control powder and the mixture of control and sample powder will give erroneous results. This test can be performed in the apparatus illustrated in Figure 10b. If the control tapped bulk density is ρ_{BTC}, up to 20 wt% of the larger unknown porous particles is mixed with the control powder and tapped in the cup of Figure 10b.

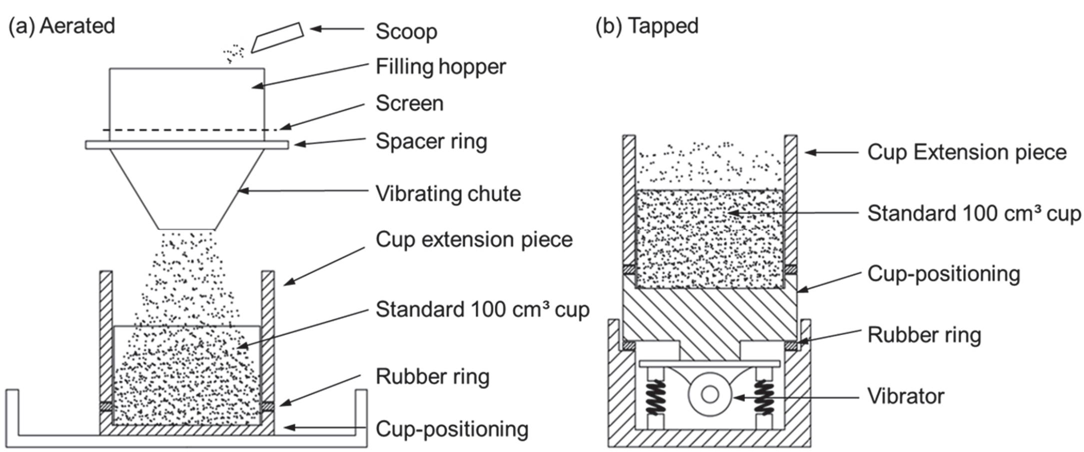

Figure 10. Measurement of aerated and tapped bulk density (adapted from [40,41]).

Additional control powder is added and tapped to completely fill the cup. The resulting mixture is weighed and as such, the added mass of control powder, M_c, is determined. With this, the particle density of the unknown particles, ρ_{pX}, is determined with Equation (40):

$$\rho_{px} = \frac{M_x}{(V - M_c/\rho_{BTC})} \tag{40}$$

with M_x being the mass of sample in the mixture and V the volume of the cup.

(7) Additionally, the minimum fluidization velocity is related to the particle density in the Ergun equation:

$$\rho_\mathrm{p} = \left[\frac{1.75}{\varepsilon_\mathrm{MF}^3} \left[\frac{d_\mathrm{sv} \nu_\mathrm{MF} \rho_\mathrm{g}}{\mu} \right]^2 + \frac{150(1-\varepsilon_\mathrm{MF})}{\varepsilon_\mathrm{MF}^3} \left[\frac{d_\mathrm{sv} \nu_\mathrm{MF} \rho_\mathrm{g}}{\mu} \right] \right] \frac{\mu^2}{d_\mathrm{sv}^3 \rho_\mathrm{g} g} + \rho_\mathrm{g} \tag{41}$$

with the subscript MF denoting the conditions at minimum fluidization velocity.

The voidage ε_MF itself is dependent on the particle density as follows:

$$\varepsilon_\mathrm{MF} = 1 - \frac{\rho_\mathrm{BMF}}{\rho_\mathrm{p}} \tag{42}$$

The solution of Equations (41) and (42) is found via an iterative procedure.

This technique proposed is only valid for spherical particles. Also, accurate values of size d_sv are required. The latter is not troublesome for spherical particles since the sieve size d_a in that case equals the surface-to-volume ratio, d_sv.

$$\rho_\mathrm{p} = \left[\frac{1.75}{\psi\varepsilon_\mathrm{MF}^3} \left[\frac{x_\mathrm{sv} \nu_\mathrm{MF} \rho_\mathrm{g}}{\mu} \right]^2 + \frac{150(1-\varepsilon_\mathrm{MF})}{\psi^2\varepsilon_\mathrm{MF}^3} \left[\frac{x_\mathrm{sv} \nu_\mathrm{MF} \rho_\mathrm{g}}{\mu} \right] \right] \frac{\mu^2}{x_\mathrm{sv}^3 \rho_\mathrm{g} g} + \rho_\mathrm{g}$$

(8) Finally, for reasons of completeness, the photographic technique is mentioned here. For a full description, the reader is advised to review the description given by Li and Iskander [42] and Grace and Ebneyamini [43]. A summary of the techniques is given in Table 11.

Table 11. Summary of methods for measurement of apparent density of particles.

Method	Relative Equipment Cost	Suitable Types of Powder in Rank Order According to Geldart's Classification
Caking end-point	Negligible	A
Mercury porosimeters	Very high	D, B, A
Comparative	Low	B, A
Gas flow	Low	A, B
Powder displacement	Low	D, B
Minimum fluidization velocity	Low	D, B, A spherical
Photographic	High	B, D, A

4.2. Bulk Density

The bulk density relates the mass of a powder to its bulk volume. With this definition, the bulk density is dependent on the size, size distribution, shape and the state of compaction of the particles. The latter can be thought of as non-material dependent, but rather as an operating or measuring condition. As such, caution must be taken that the same standardized measurement method is applied when comparing different bulk densities.

The state of compaction of the particles gives way to four categories of bulk densities: aerated or most loosely packed bulk density ρ_BLP, poured bulk density ρ_BP, tapped bulk density ρ_BT and compacted bulk density ρ_BC. For identical powders (equal composition, size, size distribution and shape), the values of the different categories of bulk density are obviously in the following order:

$$\rho_\mathrm{BLP} < \rho_\mathrm{BP} < \rho_\mathrm{BT} < \rho_\mathrm{BC}$$

Most often, only the aerated and the tapped bulked density are used.

The ratio of the tapped to the aerated bulk density is called the Hausner ratio, $\rho_\mathrm{BT}/\rho_\mathrm{LP}$, and gives a measure of the powder flowability vs. cohesivity. For instance, powders with strong interparticle forces will exhibit a relatively open structure if little or no work is done on the powder. However, tapping will compact them to a dense structure which corresponds to a high Hausner ratio. On the other hand, free-flowing powders with little or no interparticle forces will exhibit low values of the Hausner ratio. According to the Hausner ratio (R_H), powders can be classified in different categories:

- $R_H < 1.25$: Group A, B, or D
- $R_H > 1.4$: Group C
- $1.25 < R_H < 1.4$: Transition group AC

Both the aerated and the tapped bulk densities can be measured with the apparatus depicted in Figure 10. In Figure 10a, the aerated bulk density is determined by pouring the powder through a vibrating sieve which subsequently falls through the vibrating and stationary chutes into a cylindrical cup. The filling of the cup should take about 20–30 s. Any excess powder on top is removed and the cup is weighed. With the known mass of the powder, the aerated density is calculated. Next, an extension piece is attached to the full cup, as illustrated in Figure 10b. Subsequently, the cup is tapped 480 times whilst extra powder is added to fill the cup completely. After tapping, the extension is removed and excess powder on top of the cup is scraped off. Finally, the mass of the tapped powder is weighed and the tapped bulk density is calculated.

4.3. Bed Voidage

The bed voidage ε can be evaluated with Equation (29) if the particle and bulk densities ρ_P and ρ_B are known, but some general remarks about influencing factors can be made.

Factors that influence voidage are:

- The compaction state: Obviously, a tapped bed will have a smaller voidage than an aerated bed. Two extreme conditions, assuming random packing, are used as a reference: 'loose' packing with the maximum voidage and 'dense' packing with minimum voidage.
- The particle shape: The voidage increases with decreasing sphericity. This is illustrated in Figure 11.

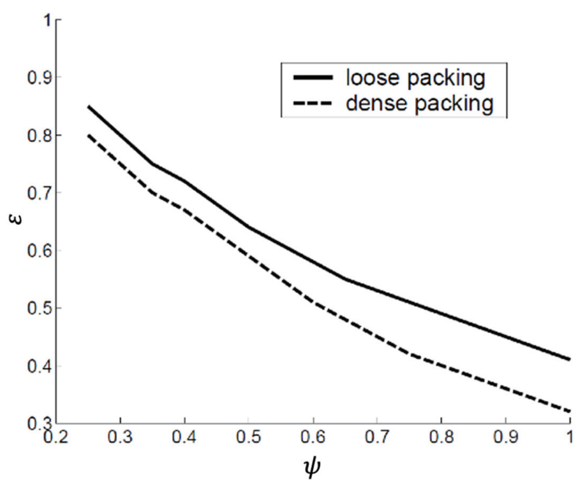

Figure 11. Voidage versus sphericity for loosely and densely packed beds of uniformly sized particles larger than about 500 μm [44].

- The particle size: For loosely packed beds, the voidage decreases with increasing particle size. The densely packed bed voidage, on the other hand, is quite insensitive to size. This is illustrated in Figure 12.

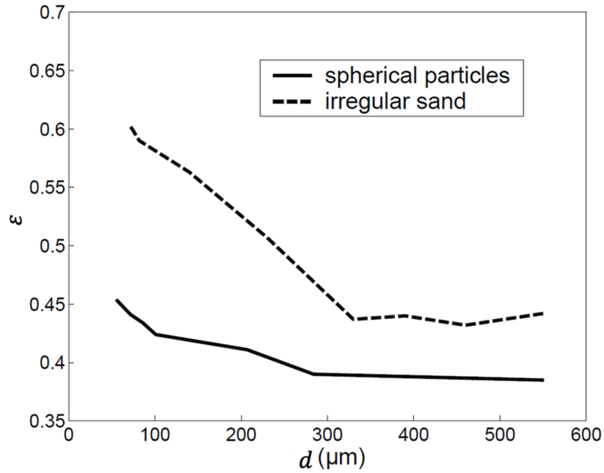

Figure 12. Variation of packed bed voidage vs. particle size for spherical particles and sand. The particle size distribution is narrow in both cases.

- The particle size distribution: The voidage decreases with increasing spread.
- The particle and wall roughness: The voidage increases with increasing surface roughness.

5. Conclusions

The design of fluid–solid processes relies on the accurate measurement of particle properties (size, size distribution, absolute and bulk density and shape).

The research discussed methods to define and measure these properties.

Particle size and its size spread is commonly measured by instrumental techniques. Recommendations towards sample size, selected solvents and dispersants and suspension mixing were defined. Size distribution functions are strongly affected by the quantity of fine particles present in the sample.

The particle shape is expressed as its sphericity. Although it is difficult to measure the sphericity, microscopic imaging or pressure drop measurements across a fixed particle bed can be used.

The absolute, apparent and bulk density of particles and powders can be determined by seven different methods. The bulk density determines the voidage of a particle assembly.

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standards

Brief Report

Building Competence in Science and Engineering

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Abstract: Next Generation Science Standards science and engineering practices (NGSS S&E) are ways of eliciting reasoning and applying foundational ideas in science. Studies have revealed one major impediment to implementing the NGSS, namely, insufficient teacher preparation, which is a concern at all teaching levels. The present study examined a program grounded in research on how students learn science and engineering pedagogical content knowledge and strategies for incorporating NGSS S&E practices into instruction. The program provided guided teaching practice, content learning experiences in the physical sciences, engineering design tasks, and extended projects. Research questions included: To what extent did the Program increase teachers' competence and confidence in science content, with emphasis on science and engineering practices? To what extent did the program increase teachers' use of reformed teaching practices? This mixed-methods, quasi-experimental design examined teacher outcomes in the program for 24 months. The professional development (PD) findings revealed significant increases in teachers' competence and confidence in integrating science and engineering practices in the classroom. These findings and their specificity contribute to current knowledge and can be utilized by districts in selecting PD to support teachers in preparing to implement the NGSS successfully.

Keywords: science; engineering; competence; teachers

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1. Building Competence in Science and Engineering Content: Research to Inform Practice

The Next Generation Science Standards (NGSS) document attempts to provide educators and students nationwide with an internationally benchmarked education by articulating conceptual science performance expectations. Little exists in implementation strategies and national studies have already identified impediments to NGSS implementation, such as the lack of resources for effective science education, limited instructional time devoted to science, and insufficient teacher training [1]. In a recent national study on teacher readiness, most middle- and high-school teachers indicated they have no engineering training and are ill-prepared to effectively implement NGSS; engineering emerged as the content area of greatest need and created the greatest degree of anxiety. Teacher preparedness is a concern at all levels as the mandates of NGSS require conceptual and exploratory learning, which are not always employed in all science classrooms [2]. There is an urgency to identify the type of professional development (PD) that will prepare teachers to meet the challenges of the NGSS. It requires an investment of resources to develop the appropriate tools to support teachers [3]. We must align the resources spent on PD with the demands teachers will face with NGSS, and also conduct the necessary research required to learn from it to inform practice.

The present study examined a program that aimed to prepare middle-school teachers for NGSS by building competence and confidence in using science and engineering practices in the classroom. We investigated PD that would potentially meet the demands teachers will face during NGSS implementation. We propose to use the information we have learned from this study's results to provide recommendations for teacher PD, as lead states begin the NGSS-adoption process.

1.1. Literature Review

Some teachers embrace an educational innovation with enthusiasm and incorporate it into their classroom teaching. Yet, others discard it and continue with their familiar teaching practices after only a few attempts [4], as all teachers are not amenable to innovation [5]. For instructors to persist in their efforts to implement new strategies, they need to have the expectation that they will succeed [5]. Individuals' beliefs about their competence and outcomes expected of their actions serve to enhance interest in a specific area, and a strong self-efficacy helps individuals overcome setbacks and persist in the face of challenge [6]. Teachers' low self-confidence and lack of competence in content become significant impediments to an innovation, such as the NGSS, as teachers will have to contend with not having the necessary equipment, materials, or training for successful implementation [1].

1.2. The Development of NGSS

NGSS is a set of science standards. Science and its fellow technology, engineering, and mathematics (STEM) disciplines are, and have been, for at least ten years, the focus of concern and reform efforts from educators nationwide [7,8]. The reasons for this are diverse. The concern that the United States is lagging behind other nations in STEM areas, and that this gap could potentially emerge as economic disaster in the future [8], has resulted in an influx of federal funding for STEM education and research, and the encouragement of institutions to pursue this research [7].

In the summer of 2011, a writing team of 41 educators worked on the first draft of the NGSS. On 9 April 2013, the finalized NGSS document was released. NGSS describe what all students should know and be able to do by the time they graduate from high school. NGSS are based on learning progressions of core ideas in the discipline, concepts that cut across disciplines and practices that will allow students to use their disciplinary knowledge in thoughtful ways. A difference from earlier 1996 standards from the National Research Council, NGSS Science and Engineering Practices are characterized as ways of identifying the reasoning behind, discourse about, and application of the core ideas in science [9].

The specific eight science and engineering practices outlined in the NGSS are: asking questions and defining problems, developing and using models, planning and carrying out investigations, analyzing and interpreting data, using mathematics and computational thinking, constructing explanations and designing solutions, engaging in argument from evidence, and obtaining, evaluating, and communicating information (2013). The process of creating the NGSS was driven by 26 lead states that contributed resources and provided support. They are expected to be trailblazers in the adoption of the NGSS. However, the choice to implement curricula and the form these curricula will take is ultimately at the discretion of individual states.

1.3. NGSS, Models, and Modeling Instruction

Recent research contributes to current understanding of how students develop and use models in middle- and high-school classrooms. Current modeling research has focused on argumentation in science education [10,11], model-based inquiry [12], software scaffolds supporting modeling practices [13] constructing and revising models [14], and integrating conscious and intuitive knowledge [15].

Educators often discuss the important role models play in science education [16]. Scientific disciplines are guided in their inquiries by models that scientists use to create explanations for data and to further investigate nature. The design, use, assessment, and revision of models and related explanations play a primary role in scientific inquiry and should be a prominent feature of students' science education [12].

Researchers investigating modeling nationally and internationally have significantly influenced the conceptualization of modeling articulated in NGSS [13,14]. They have advocated for the role of models and modeling in school science, and also argue that modeling is a core practice in science and a central part of scientific literacy [13]. Scientific modeling includes the elements of the practice (constructing, using, evaluating, and revising scientific models) and the knowledge that guides and motivates the practice such as understanding the purpose of models [13].

NGSS [17] employs the use of core-science and engineering practices (identified above), which are at the foundation of modeling instruction, an evidence-based pedagogy for science education that was developed in the 1980s. Modeling instruction integrates a student-centered teaching method with a model-centered curriculum [18,19]. It applies structured-inquiry techniques to teaching fundamental skills in mathematical modeling, proportional reasoning, and data analysis, which contribute to critical thinking, including the ability to formulate hypotheses and evaluate them with rational argument and evidence.

Modeling pedagogy has three elements: the models, the modeling cycle, and classroom discourse management [18,19]. An understanding of these elements is the pedagogical content knowledge [20] needed for successful classroom adoption and implementation. A model is a representation of structure—a conceptual representation of a real thing [18,19]. The models around which learning is centered in modeling are basic relationships among quantities that form the content core of a discipline and these models are developed by students into tools for making sense of physical reality—for making predictions.

Modeling has been defined as an activity. With its foundation in the modeling cycle [18,19] is a three phase process: model construction, which takes place in the context of a paradigm lab that discovers a link between two physical quantities at the beginning of each instructional unit; model validation, in which students refine the basic model they have constructed by testing it in disparate initial conditions; and model deployment, in which students use the model to solve problems from diverse contexts.

Teachers learn modeling instruction by participating in a modeling workshop—an intensive, three-week 90-h immersion experience. Teachers are engaged in laboratory investigations and activities, creating experiments, collecting, analyzing, interpreting data, and engaging in classroom discourse to achieve collective sense-making. It is by active participation in the discourse that characterizes the modeling learning that teachers can become effective managers of modeling discourse in their classrooms. modeling instruction began in college and high school physics and has expanded across the science disciplines into chemistry, biology, physical science and middle school science.

1.4. Study Overview

This study examines in-service teachers' outcomes in a program that aimed to increase teachers' content knowledge (cognitive skill) and confidence (self-efficacy) in the use of science and engineering practices (SEP) in the classroom. Three high-needs districts and a state university formed a partnership and proposed to enhance the quality of science instruction for middle-school teachers. The partnership was cognizant of the fact that science instructors lacked adequate preparation in areas associated with science and engineering practices and proposed, through the use of modeling instruction, to increase teacher science-content knowledge of energy and matter. The team planned a formal needs assessment in 2012 to collect data on concrete deficiencies.

1.5. Needs Assessment Identifies Professional Development Focus

A survey was administered to partnership teachers to assess their knowledge related to the grant's content focus. An online survey was administered in summer, 2012 to 250 science and math instructors in three districts to assess their science content knowledge with emphasis on SEP. The survey yielded a 68% response rate (n = 171). The assessment revealed that teachers in grades six through eight had the following limitations: lack of content knowledge and confidence in their ability to teach science content, with emphasis on scientific and engineering practices; minimal knowledge on integrating science and engineering content; and limited knowledge of how to design and deliver science and engineering activities. Teachers had no college coursework in the structure of matter, matter and energy flow in organisms, conservation and transfer of energy, the relationships of energy and forces, and energy in everyday life. This corresponded to no physics, chemistry or biology courses that could be considered fundamental to NGSS standards and practices.

The data were combined with research that highlights the correlation between teachers' science-content knowledge and student achievement [20] and SEP and student achievement [21,22], particularly in high poverty areas, which were project cornerstones. Teacher deficiencies were a concern in these districts and administrators wanted to identify PD to best train teachers to meet NGSS challenges.

Based on the needs assessment, partners identified three goals targeting middle-school teachers: increase teachers' physical science content knowledge in energy and matter; increase teachers' confidence in incorporating NGSS SEP into their instruction; and increase teachers' use of reformed teaching practices.

1.6. Professional Development Model

The PD model was designed to move the partnership toward accomplishing these goals, which started 27 October 2012 and was completed by Summer of 2014. PD included 236 h with three six-hour Saturday PD sessions during each academic year and two three-week summer institutes in 2013 and 2014. Teachers participated in 227 h of PD overall. The Partnership for Success (PAS) program engaged 27 teachers in grades six through eight. The practices of engineering design were interrelated with scientific practices to create the context of the learning environment. PAS provided teachers with a PD program grounded in research on how students learn science and engineering pedagogical content knowledge and strategies for incorporating NGSS S into instruction. To do so, PD provided guided teaching practice, content learning experiences in the physical sciences, and engineering design tasks and extended projects. modeling instruction was also integrated into the PD model.

PAS activities were selected to provide teachers with content preparation in a core scientific concept—energy—and to provide explicit practice and experience in using SEP. Teachers worked through activities and sense-making, confronting misconceptions, and learning to argue from evidence just as their students will be expected to do. They engaged in classroom discourse that reflected the type of discourse they would be expected to mediate in their own classrooms. Teachers went from "student mode," in whole-group discussions, to "teacher mode" deliberations, in which they explored the instructional implications and identified the theoretical underpinnings and disciplinary links to what they were learning. As PAS participants were middle-school teachers, faculty often helped them appreciate both the horizontal continuum of the energy concept across disciplines, and the vertical trajectory of conceptual development across grade levels, which resulted in a coherent model of energy storage and transfer.

Both summers focused on crosscutting models of energy and the structure of matter. The first summer institute delved into macroscopic models of energy and the structure of matter and focused on developing SEP in the context of motion, forces, and mechanical and gravitational energy. Time was given to the development of operational definitions the use of scientific language and management of classroom discourse. Saturday sessions, after this first Institute, gave teachers an opportunity to share their successes and challenges as they gained confidence in the use of new teaching strategies. PAS engaged them in additional engineering design activities to help them transition from macroscopic to microscopic models of energy and the structure of matter to help frame the content for the second summer. The second summer institute focused on chemistry, ecology, and the earth sciences. More time was spent understanding the structure of matter and the role of energy and systems in these content areas.

The mechanism used to deliver instruction was the Modeling Method of Instruction. The design of instruction followed the modeling cycle, thus, participants engaged in whole group pre-laboratory discussions and small-group laboratory activities, followed by analysis and synthesis of results. These results were shared via whiteboard meetings—whole group discussion and sense-making around the relationships explored in the laboratory activities. This model construction activity was then followed by a series of model elaboration and deployment activities. Activities done in small groups were followed by whole group discussion to allow participants to place what they learned in the context of their own teaching assignment.

Iterative engineering design activities were used as a capstone activity in the summer institute. Teachers were involved in a guided curriculum design activity in which they worked together in groups. They used the modeling cycle to design or redesign a curriculum unit of their choosing and incorporated activities that utilized SEP. Units designed by participants were also made available electronically to other participants so they could integrate them in their own classrooms with the goal of giving feedback to the unit designer.

1.7. Partner Roles

District personnel were responsible for basic communication, facilities and district credit, as well as overall project management. University personnel were responsible for initial planning and delivery of professional development. The researcher was responsible for collection and analysis of aggregated data, quarterly reports (formative assessment), and dissemination of findings in a summative report. While each partner in the project had these specific roles, PD curriculum, leadership in PD sessions, data collection and analysis, and production of project deliverables were accomplished in full cooperation and participation.

2. Method

2.1. Research Design

This study employed a mixed-methods approach and thus the investigator collected, analyzed, and drew inferences from both quantitative and qualitative data in a single study. The investigator held the assumption that the combination of quantitative and qualitative approaches provides greater understanding of the research problem than either approach alone [23]. The researcher used a quasi-experimental, matched-comparison group design, using multiple methods and statistical tests to measure progress toward meeting the established outcomes. This model provides a good alternative, as a randomized controlled trial was not feasible. The research design included both quantitative and qualitative methods and employed analysis of variance (ANOVA) to determine differences between groups and qualitative analysis to code, categorize, and analyze teacher comments. The assumptions of homogeneity of variance, normality, and independence were tested and met.

Research questions that guided the study included:

1. To what extent did the program increase middle school teachers' science content knowledge, with emphasis on science and engineering practices?
2. To what extent did the program increase middle school teachers' self-confidence in teaching science content, with emphasis on science and engineering practices?
3. To what extent did the program increase teachers' use of reformed teaching practices?

2.2. Participants and Recruitment

District and school administrators developed strategies for the PAS program for recruitment and retention of teachers to maintain samples size of both groups (experimental and comparison groups). In year one, the project team recruited over 30 participating teachers from the three districts in the partnership and a comparison group equivalent on selected demographic characteristics (i.e., time teaching, grade band, and area of specialization). Matched comparison was based on number of years teaching (average of 13 years), grade level taught (i.e., middle school), and area of specialization (i.e., science). A t test analysis revealed no statistical difference between the groups based on the number of years teaching and grade level.

2.3. Quantitative Data

Data Sources. In order to answer the first research question (To what extent did the Program increase middle school teachers' science content knowledge, with emphasis on science and engineering practices?) the investigator employed the Diagnostic Test for Mathematics and Science (DTAMS) as a pre–post measure, and it was administered to both groups. In addition, the Basic Energy Concept Inventory (BECI) served as a pre–post measure for the PAS group, as it was closely aligned to the intervention. The BECI, a 25-selected-response-item instrument, is used to capture commonly held misconceptions regarding energy.

To answer the second question (To what extent did the Program increase middle-school teachers' confidence in science content, with emphasis on science and engineering practices?) a self-efficacy instrument, the Science Teaching Efficacy Beliefs Instrument or STEBI [24] was administered to both groups as a pre–post measure. The STEBI, with 24-items, assessed teachers' confidence in science and engineering practices using a 5-point Likert scale (5 = strongly agree to 1 = strongly disagree).

To answer the third research question (To what extent did the Program increase teachers' use of reformed teaching practices?) an observational tool, the Reformed Teacher Observation Protocol (RTOP, [25]) was used as a pre–post measure for both groups. The RTOP, a 25-item observational instrument, was designed to measure reformed teaching as defined by research in mathematics and science and national standards. All pre assessments were administered to both groups before the start of the intervention and the post-tests were administered to both groups after the intervention ended for the experimental group.

As another data source, an online survey was administered after each Saturday PD session and during the summer institutes. Teachers rated PAS in terms of its effectiveness in providing guidance and concrete examples to enable progress in the eight NGSS SEP. The survey used a five-point rating scale of effectiveness (5 = highly effective, 4 = effective, 3 = average, 2 = below average, and 1 = not effective).

Data Analysis. Quantitative data were analyzed two ways. Analysis of variance (ANOVA) determined differences between groups. Secondly, a paired samples t test was used to examine difference within groups to determine program efficacy. All analyses include 27 PAS and 29 comparison teachers. The assumptions of homogeneity of variance, normality, and independence were tested and met.

2.4. Qualitative Data

Teachers were given the opportunity to comment (on surveys) on the PAS program after each Saturday PD and during the summer institutes. They were asked to rate the program on specific criteria such as providing training on NGSS SEP but could also express views about PAS impact; as a result, themes associated with NGSS competence, confidence, and implementation in the classroom emerged. The researcher used the constant comparative method [26] as a conceptualizing method on the first level of abstraction. The initial phase involved conceptualizing all the incidents in the data. The researcher compared data and continually modified and sharpened the growing theory at the same time. Notes were compared to find differences and consistencies between codes, which helped reveal categories. Data were analyzed using a three-step process: data reduction, data display, and conclusion drawing and verification [27,28]. Data reduction helped to sort, focus, and condense excerpts, which helped organize the data to develop conclusions. Data display enabled review of the reduced data so that conclusions could be drawn. Teachers' excerpts formed the basis for identifying categories, themes, and assertions.

2.5. Quantitative Results

To answer the first research question (To what extent did the Program increase teachers' science content knowledge, with emphasis on science and engineering practices?) the DTAMS was employed. The DTAMS pre–post test was used to measure knowledge of core content concepts. Means are arrayed for the PAS and comparison groups in terms of pre–

post test within each group (paired *t* tests) and post-test statistical comparisons between the groups (ANOVA) to determine differences. PAS significantly outscored the comparison group on the DTAMS content knowledge items and the difference was significant ($p = 0.03$).

2.6. DTAMS Results

Between Group Difference. This evaluation examined differences between groups on the DTAMS' overall-content-knowledge mean score. The overall possible score for the content knowledge was 35. The PAS group (27 teachers) final knowledge mean score was 18.22 (SD = 5.4) and the comparison group (29 teachers) final knowledge mean was 15.31 (SD = 4.78), which revealed a significant difference favoring the PAS group ($p = 0.03$) as shown in Table 1 below.

Table 1. DTAMS: Group Comparison Post-Means.

	PAS Post-DTAMS	**Comparison Post DTAMS**
	Mean (SD)	**Mean (SD)**
DTAMS Means	18.22 (5.40)	15.31 (4.78) *

* $p < 0.05$.

Within Group Differences. For PAS, there was a modest gain from the pre- (M = 16.62, SD = 5.26) to post-DTAMS knowledge mean (M = 18.22, SD = 5.40) and the gain was not significant ($p = 0.27$). There was no significant difference for the comparison group from the pre-DTAMS knowledge mean (M = 16.20, SD = 5.0) to post-DTAMS mean (M = 15.31, SD = 4.78) ($p = 0.51$), as seen in Table 2 below. There was no significant difference between the PAS and the comparison group on the pre-DTAMS knowledge mean score ($p = 0.75$).

Table 2. DTAMS: Within Group Comparison Pre-Post DTAMS Means.

	Pre-DTAMS	**Post DTAMS**
	Mean (SD)	**Mean (SD)**
PAS Teachers	16.62 (5.26)	18.22 (5.40)
Comparison Teachers	16.20 (5.00)	15.31 (4.78)

2.7. Basic Energy Concept Inventory (BECI) Results

To answer the first research question, the Basic Energy Concept Inventory (BECI), an instrument to capture commonly held misconceptions regarding energy, was administered to the PAS group. The PAS program focused on energy content, and the BECI instrument was considered well aligned to the PAS intervention. Initially, teachers did not understand the structure of matter or potential energy, the structure of matter well enough to account for both warmth and coldness in terms of thermal energy, and did not account for energy that had dissipated into the environment. For the PAS administration of the pre- and a post-BECI, post-scores were higher (M = 15.7, SD = 3.03) than on the pre-BECI (M = 8.7, SD = 3.79) and the difference was significant ($p < 0.001$). Teachers mastered 63% of energy content (see Table 3).

Table 3. BECI: PAS Group BECI Pre-Post Difference.

	PAS Pre-Test	**PAS Post-Test**
	Mean (SD)	**Mean (SD)**
BECI Means	8.70 (3.79)	15.7 (3.03) *

* $p < 0.0001$.

The overarching themes of the PAS workshops were energy and the structure of matter. Special care was taken, during the course of these workshops, to develop representational tools and practices that allowed the teachers to develop robust models of microscopic and macroscopic models of both of these core concepts, and teachers were encouraged to employ these tools across disciplines and grade levels. BECI increases revealed that PAS teachers left the program with a more robust microscopic model of energy transfer and storage.

2.8. Self-Efficacy Instrument Results

To answer the second question (To what extent did the Program increase middle school teachers' confidence in science content, with emphasis on science and engineering practices?) a science teaching self-efficacy instrument was administered. Teachers had increased confidence in science and engineering practices and the ability to design and deliver engineering activities. In addition, teachers were less anxious about their engineering skills.

Within-Group Differences. Post-survey means revealed PAS teachers were more confident in their ability to design and deliver science and engineering activities and integrate SEP into their classroom. Data revealed teachers were less anxious about their engineering skills and more confident in the following areas: having the ability to answer students' engineering questions (survey item 18); using SEP to enable integration into classroom instruction (survey item 19); and designing and delivering engineering activities (item 23). PAS teachers were more confident in designing and delivering science content with scientific and engineering practices (SEP) (p-value < 0.001), as seen in the Appendix A.

The increase in self-confidence for PAS teachers was also evident in the everyday actions of the teachers in the second year Saturday sessions and during the final summer institute regarding the depth and the types of questions they asked. There was an increase in teacher directed inquiry and analysis at the end of an activity. In addition, teachers were able to think deeply about what they were doing (during and after experiments) and about student thinking and learning in the context of engineering content and practices. In many instances, teachers were able to make suggestion on how to make the activities better.

Between Group Differences. There were differences between groups on the post self-efficacy survey relating to items on SEP and engineering skills, favoring PAS. Post-survey means showed PAS teachers were more confident ($p < 0.01$) in their ability to answer students' engineering questions (M = 3.66, SD = 0.62) than the control (M = 3.03, SD = 1.14). PAS teachers were more confident ($p < 0.001$) in using SEP to enable integration into classroom instruction (M = 4.03, SD = 0.75) than the control (M = 3.24, SD = 1.02) and were more confident ($p < 0.001$) in designing and delivering science content with SEP (M = 4.11, SD = 0.75) than the comparison group (M = 3.00, SD = 1.30) as seen in Table 4.

Table 4. Self-efficacy instrument post means: PAS and comparison group differences [1].

Scientific and Engineering Practices Self-Efficacy Survey Item		PAS Post		Comparison Post	
		Mean	SD	Mean	SD
18	I am typically able to answer students' engineering questions	3.66	0.62	3.10	1.17 *
19	I am confident in using Scientific and Engineering Practices to enable integration into classroom instruction	4.03	0.75	3.24	1.02 **
20	I am typically anxious about my engineering skills	2.66	1.17	3.00	1.06
21	I currently have the necessary skills to integrate Scientific and Engineering Practices	4.00	0.73	3.06	1.25 **
22	I am currently able to design and deliver science activities	4.30	0.60	3.82	1.28
23	I am currently able to design and deliver engineering activities	3.77	0.89	3.17	1.07 *
24	I am currently able to design and deliver science content with science & engineering practices	4.11	0.75	3.00	1.30 **
Degree of Agreement (5 = strongly agree to 1 = strongly disagree)		$n = 27$		$n = 29$	

* p-value = 0.01, ** p-value $\leq$ 0.001, [1] Independent-samples t-test.

PAS PD in NGSS Scientific and Engineering Practices: Survey Results. To determine the extent to which PAS provided strategies and guidance to increase competence and confidence in NGSS SEP, an online survey was administered. Overall, the majority of teachers felt the program was highly Effective in providing guidance and examples in the following SEP: developing and using models (81% highly effective), engaging in argument from evidence (70%), asking questions and defining problems (67%), analyzing and interpreting data (67%), obtaining, evaluating and communicating information (67%), and planning and carrying out investigations (58%) as seen in Table 5 below.

Table 5. PAS Provided effective training in NGSS science and engineering practices.

PAS Provided Guidance and Examples in	**Teacher Rank of PAS Guidance and Providing Examples (%)**				
	Highly Effective	**Effective**	**Average**	**Below Average**	**Not Effective**
Asking questions/defining problems	67%	30%	3%		
Developing and using models	81%	19%			
Planning investigations	58%	42%			
Analyzing/interpreting data	67%	30%	3%		
Using math/computational thinking	19%	78%	3%		
Construct explanations/design solutions	33%	67%			
Engaging in argument from evidence	70%	30%			
Obtaining, communicating information	67%	33%			

2.9. Reformed Teacher Observation Protocol (RTOP)

To answer the third research question (To what extent does the project increase participating teachers' use of reformed teaching practices?) the RTOP was employed as the classroom observational tool. The post-RTOP data and significant differences (from pre- to post-RTOP) for the PAS group revealed integration of practices such as developing and using models, engaging in argument from evidence, asking questions and defining problems and analyzing data. The PAS group outscored the comparison group on the post-RTOP revealing growth over time, and also highlighted PAS teachers' increased integration of NGSS S&E practices.

Within-Group Differences. The PAS group post-RTOP score (M = 73.44, SD = 14.32) revealed a 22-point gain from the pre RTOP score (M = 51.41, SD = 22.43) and the gain was significant ($p < 0.001$) as seen in Table 6 below. There was no significant difference for the Comparison group regarding the pre–post RTOP scores ($p = 0.47$). No significant difference was evident between the PAS and the Comparison groups on the pre-RTOP scores ($p = 0.30$).

Table 6. RTOP: Within group comparison pre–post means.

	Pre-RTOP	**Post RTOP**
	Mean (SD)	**Mean (SD)**
PAS Teachers	51.41 (22.43)	73.44 (14.32) **
Comparison Teachers	57.38 (20.51)	56.10 (19.04)

** $p < 0.001$.

Between Group Differences. There was a significant difference between groups on the post RTOP scores ($p = 0.0003$) favoring PAS as seen in Table 3. The mean for the PAS group was 73.44 (SD = 14.32) and the mean for the Comparison was 56.10 (SD = 19.04). There was a Cohen's d 'large' effect size of 0.80, or one standard deviation difference between groups.

RTOP data revealed PAS teachers' use of reformed teaching practices. Specifically, growth was observed in teachers' integration of NGSS SEP as students were seen developing and using models, engaging in argument from evidence, asking questions and defining problems, and analyzing and interpreting data. PAS classrooms, during post-RTOP observations, frequently involved students developing explanations and employing critique and evaluation (promoting argumentation from evidence). Increases also emerged as students incorporated (RTOP, 9) elements of abstraction with symbolic representations and theory building. Also, (RTOP, 11) students used a variety of means and developed and used models (e.g., used models, drawings, graphs, and concrete materials to represent phenomena); asked questions and defined problems; made more predictions, estimations, and hypotheses, and devised means for testing them (RTOP, 12); communicated information and ideas to other using a variety of means (RTOP, 16) and were analytical and reflective in their learning (RTOP, 14).

3. Qualitative Results

NGSS Implementation in the Classroom

Comments indicated that when teachers started the program, they had "increased anxiety over NGSS requiring a new set of skills not found in their education" yet PAS "provided a new skill set" (C. Mason, survey response, June, 2014). Initial teacher comments (commenters' names have been replaced by pseudonyms in this section) revealed anxiety associated with insufficient teacher training for successful NGSS implementation, impediments, which were similar to those identified in a prior study [1]. In addition to low self-confidence, the comments focused on lack of engineering content knowledge and the inability to design and deliver integrated science and engineering activities. Qualitative comments captured at the end of the program indicated teachers were more frequently embedding NGSS SEP in the classroom, as reflected in the following excerpt, "Before the PAS program, I did not integrate any engineering practices. Now, I incorporate engineering practices almost on a weekly basis. This has been an easy transition especially with the models, resources, and strategies provided by the program" (A. Sabato, survey response, June, 2014). Another echoed this sentiment, "Now I have many strategies to integrate science and engineering practices and I use models, graphs, and other elements of abstraction in my teaching (M. Rodriguez, survey response, June 2014). Another indicated, "I feel much more confident in using science and engineering practices and asking students to use models, analyze data, and be reflective in their learning" (B. Masters, survey response, June 2014). Teachers more often used "scientific writing, integrating claim, evidence, and reasoning into classroom projects" (A. Prosser, survey response, 27 June 2014) and required students to "ask questions, analyze and interpret data, and communicate information during class time" (A. Monroe, survey response, 27 June 2014). The majority of teachers use modeling instruction and ask students to "define problems, build and use models, collect and analyze data, and communicate information to classmates."

Teachers provided details on how they were integrating NGSS SEP into the classroom. One noted, "I use models and modeling instruction in my classroom and allow students to build their own conceptual models. I have changed my expectations for my students' lab reports and we focus on claims, evidence and reasoning" (T. Walker, survey response, 28 June 2014). Others have re-engineered the way they structure classes as a strategic process "Students have been involved in more experiments, and will be engaged in more open experimentation that will foster greater analysis and communication individually and between students" (A. Verde, survey response, June 2014). "PAS content and pedagogy have increased student critical thinking, confidence, and engagement" (C. Lorenzo, interview response, June 2015). Teachers are "promoting more student critical thinking and allow students to guide learning." They have devoted more time to planning the inquiry line of questioning.

4. Discussion

National research suggests that there are several impediments to overcome for the adoption of NGSS and one barrier is inadequate teacher preparation [1]. Similarly, the PAS partnership recognized local teachers lacked adequate training in areas associated with science and engineering practices and proposed, through modeling-based learning experiences, to increase content knowledge in energy and matter. This study examined

PAS efficacy and found that the PD potentially meets the demands middle-school teachers will face during NGSS implementation. PAS PD, which provided integrated science and engineering content, guided teaching practice, content learning experiences in the physical sciences, and engineering design tasks, increased teachers' competence and confidence in using NGSS SEP. It is likely these results will help inform other educators and researchers as states and district begin the NGSS adoption process.

4.1. Program Builds Competence and Confidence in the Use of NGSS

Although current science teaching practices often emphasize the memorization of facts, the PAS team adopted the NGSS focus, which emphasizes the active construction of conceptual knowledge by "doing science" through science and engineering practices. Regarding content, the BECI attempted to capture gains in energy and the structure of matter, which were the overarching themes in PAS. PAS required the development and use of representational tools and practices that allowed teachers to develop microscopic and macroscopic models of these core concepts. Teachers were involved in deep, rich discussions to highlight naïve beliefs and replace them with coherent conceptual models. Using models as thinking tools in diverse problem contexts, teachers used them to frame their thinking in responding to BECI questions. Moreover, BECI increases revealed that PAS teachers left the program with a more robust microscopic model of energy transfer and storage.

PAS data revealed increased self-confidence as teachers were less anxious about their engineering skills and more confident in their ability to answer students' engineering questions; were more confident in using scientific and engineering practices to enable integration into classroom instruction and in designing and delivering engineering activities. They also indicated they were better able to design, deliver, and integrate science content with SEP.

4.2. Program Teachers Use NGSS SEP in Classroom Instruction

During observations, PAS teachers were guided in their inquiries by models, which often created explanations for data. In addition, teachers' design, use, assessment and refinement of models played a primary role in the program, supporting NGSS and prior research emphasizing the importance of models in science education [11,14,16]. Consistent with international and national research informing the NGSS, PAS made modeling a core practice in the PD [13,14]. PAS was also found effective integrating argumentation [10]; using model-based inquiry [12]; planning and carrying out investigations; constructing explanations and designing solutions; and obtaining, evaluating, and communicating information, thereby supporting NGSS [17].

5. Limitations

PAS program teachers were recruited by the three districts and were paid for their participation. Teachers self-selected into the study, and these teachers persisted in a PD program for 24 months. Since the teachers were not randomly selected, there are limitations to the study; teachers were motivated to learn new skills and persist in the program. These results may be generalizable to the population of teachers who would enroll in PD for academic growth and for those who are dedicated to improving their NGSS scientific engineering and practices.

6. Implications

PAS teachers were more competent and confident in using science content that emphasized science and engineering practices in the classroom. What implications are relevant to states adopting NGSS and districts serving middle school students? These findings and their specificity contribute to current knowledge and can be utilized by districts in selecting PD to support teachers in preparing to implement NGSS successfully. Teachers trained in the methods above and those who employ modeling instruction offer a profile of teachers who could become leaders in NGSS teacher professional development. They could also be employed as peer mentors in schools and districts to facilitate the transition to and implementation of the new standards. As NGSS move towards national adoption, it is crucial that educational leaders understand what these standards and the changes will mean for the teachers who implement them. To this end, our study examined a program that aimed to prepare middle-school teachers for NGSS by building competence and confidence in using science and engineering practices. This PD, incorporating modeling instruction, potentially meets the demands teachers will face during NGSS implementation. Our findings support prior research on elementary teachers, adding to the literature base on NGSS implementation. Consistent with results from Trygstad [1], our findings call for targeted professional development as teachers are concerned about receiving training in engineering content. The information we have learned from this study will help educators align the resources spent on PD with the demands teachers will face in a NGSS classroom.

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Appendix A

Table A1. Self-Efficacy Instrument: PAS Pre-Post Results.

	Self-Efficacy Survey Item	PAS Pre		PAS Post	
		Mean	SD	Mean	SD
1	When a student does better than usual in science, it is often because the teacher exerted a little extra effort	3.51	1.05	3.88	0.69
2	I am continually finding better ways to teach science	4.0	1.17	4.48	0.84
3	When the science grades of students improve, it is most often due to their teacher having found a more effective teaching approach	4.0	0.88	4.18	0.55
4	I know the steps necessary to teach science effectively	3.37	1.19	4.03	0.70
5	I am effective in monitoring science & engineering experiments	2.14	0.66	4.07	0.72 **
6	If students are underachieving in science, it is most likely due to ineffective science teaching	3.37	0.79	3.18	1.03
7	The inadequacy of a student's science background can be overcome by good teaching	3.7	0.86	3.88	0.84
8	The low science achievement of some students cannot generally be blamed on their teachers	2.92	0.91	3.37	0.96
9	When a low achieving child progresses in science, it is usually due to extra attention given by the teacher	3.62	0.92	3.85	0.71
10	I understand science concepts well enough to be effective in teaching elementary science	3.96	0.93	4.55	0.57 *

Table A1. *Cont.*

	Self-Efficacy Survey Item	PAS Pre		PAS Post	
		Mean	SD	Mean	SD
11	I understand science concepts with science & engineering practices to be effective in teaching middle school science	2.19	0.73	4.11	0.93 **
12	Teacher is responsible for student achievement in science	3.48	0.89	3.74	0.90
13	Students' achievement in science is directly related to their teacher's effectiveness in science teaching	3.63	0.83	3.55	0.97
14	If parents comment that their child is showing more interest in science at school, it is probably due to the performance of the child's teacher	3.70	0.77	4.11	2.07 *
15	It is difficult explaining to students why science experiments work	1.85	0.86	2.07	0.67
16	Effectiveness in science teaching has little influence on the achievement of students with low motivation	2.37	1.11	2.33	0.83
17	I am typically able to answer students' science questions	4.0	0.91	4.15	0.53
18	I am typically able to answer students' engineering questions	1.92	0.67	3.66	0.62 **
19	I am confident in using Scientific and Engineering Practices to enable integration into classroom instruction	1.92	0.67	4.03	0.75 **
20	I am typically anxious about my engineering skills	4.07	0.72	2.66	1.17 **
21	I currently have the necessary skills to integrate Scientific and Engineering Practices	2.14	0.90	4.00	0.73 **
22	I am currently able to design and deliver science activities	3.59	1.04	4.30	0.60
23	I am currently able to design and deliver engineering activities	1.92	0.82	3.77	0.89 **
24	I am currently able to design and deliver science content with science & engineering practices	1.62	0.62	4.11	0.75 **
	Degree of Agreement (5 = strongly agree to 1 = strongly disagree)	*n* = 27		*n* = 27	

* p-value $\leq$ 0.05, ** p-value < 0.001. Wilcoxon test (nonparametric) 107172044.

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standards

MDPI

Article

Mathematical Standard-Parameters Dual Optimization for Metal Hip Arthroplasty Wear Modelling with Medical Physics Applications

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Abstract: Total hip metal arthroplasty (THA) constitutes an important proportion of the standard clinical hip implant usage in Medical Physics and Biomedical Engineering. A computational nonlinear optimization is performed with two commonly metal materials in Metal-on-Metal (MoM) THA. Namely, Cast Co-Cr Alloy and Titanium. The principal result is the numerical determination of the K adimensional-constant parameter of the model. Results from a new more powerful algorithm than previous contributions, show significant improvements. Numerical standard figures for dual optimization give acceptable model-parameter values with low residuals. These results are demonstrated with 2D and 3D Graphical/Interior Optimization also. According to the findings/calculations, the standard optimized metal-model parameters are mathematically proven and verified. Mathematical consequences are obtained for model improvements and in vitro simulation methodology. The wear magnitude for in vitro determinations with these model parameter data constitute the innovation of the method. In consequence, the erosion prediction for laboratory experimental testing in THA adds valuable information to the literature. Applications lead to medical physics improvements for material/metal-THA designs.

Keywords: dual nonlinear optimization; metal artificial implants (MAI); hip implants; total hip arthroplasty (THA); MoM (Metal-on-Metal hip implant); objective function (OF); prosthesis materials; wear; biomechanical forces

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1. Introduction

In general, there are currently three material groups widely used in total hip metal arthroplasty (THA). Namely, ceramic, metal, and polyethylene. The principal components of a THA are cup and head. Clinically, head-cup combinations could be even (CoC, MoM) or uneven (PoM, CoM, PoC). When a polyethylene cup constitutes at least one component of the THA, the bearing is considered soft [1–4], otherwise the bearing is hard. The wear of the THA implant occurs in-between the head and cup, specifically in erosion and abrasion biotribological phenomena. This biotribological wear-interface is based on complex biomechanical forces distribution and was presented in previous publications [1,2].

Biomaterials in orthopaedics have evolved significantly along several generations [4–8]. Ceramic materials is the generic group whose hardness magnitude is highest. It is followed in order of magnitude by the metal group and then the polyethylene one. In THA research, the wear/changes during post-operational and implant lifetime in patient can be clinically measured in vivo by using a number of imaging techniques available [3,9]. These are usually conventional XR, RSA (radiostereometric analysis), CT (computerized tomography), MRI (magnetic resonance imaging), and variants/combinations of these. Computational geometry, based on imaging systems, can obtain THA post-surgical and long-term evolution, checking the implant fit with radiomarkers. There are geometrical methods based on radiomarkers positioning to get precise evaluations of the implant up-to-date condition(s). For instance, radiomarkers for pre- and post-surgical positioning determination of lumbar artificial disks were clinically/industrially developed [2].

For in vitro THA wear simulations, the methods conjoin experimental work with modelling optimization. The correlation between in vitro and in vivo data-matching is rather difficult. Since the biomechanical loads are combined with almost continuous/variant daily moving and personal dynamics habits at any physical activity, the THA erosion wear constitutes a biomedical complicated factor. The approximate magnitude of its wear along usage-time has to be determined when manufacturing/designing any THA—no matter metal, ceramic, or polyethylene. Metal prostheses/materials are subject, in general, to erosion and corrosion physical of chemical phenomena, and tribocorrosion happens on human plasma medium, when corrosion, due to plasma free radicals, becomes synergic with erosion. Other types of complications are caused by debris particles of the eccentric wear in the acetabular cup or the cup dislocation [10] when bone hardness is weak and screws cannot hold sufficiently. The in vitro experiment of THA devices to obtain tentative/precise erosive data is an important stage in the manufacturing process. However, and additionally, the in vivo measurements differ from the lab experiments. If the THA prostheses fail, post-operative complications could be a serious surgical problem.

Therefore, the use of mathematical models represents a useful/efficacious tool for these predictions. The continuous improvements in modelling, both analytical and in finite elements, is performed with the combination of computational bioengineering meshed with experimental data. In previous contributions [1,2], a number of optimization models were developed with computational-mathematical methods. In consequence, the principal objective of this study was to obtain advances in an analytical model. This result is the numerical determination of the K adimensional-constant parameter of the model.

Formerly [1], a classification of clinical factors related to THA surgery were presented. Namely, the PF-TCF Hip Arthroplasty Functional Treatment Classification [1]. PF are factors depending on the patient, and TCF are technical-clinical factors of the hospital and/or traumatology-orthopedics service.

In summary, this study presents and demonstrates a mathematical optimization method(s) for in vitro wear prediction in dual metal THA, titanium, and cast Co-Cr alloy. A 3D algorithm is developed and then fitted to experimental data. Computational software method(s) are explained and proven. Applications on Medical Physics and Biomedical engineering emerge from the mathematical results.

Theoretical and Clinical Biomechanics THA Modelling Pathogenesis with Physics Fundamentals

The pathogenesis of hip articulation malfunction is caused statistically mostly by the high incidence/prevalence of femur neck fracture due to osteoporosis. This happens usually in elderly patients. This incidence/prevalence increases in developed countries in correlation with the increment of the average population age and lifetime expectancy. According to statistics in the European Union and Europe, Germany and Switzerland are the countries where a higher number of THA are surgically implanted/fixed [11,12].

Given a femur neck with osteoporosis [11], as shown in Figure 1, the fracture happens because the head and trochanter are united by the neck, which is the weakest and thinnest bone zone. In addition, the hip load over the femur head causes a mechanical torque whose arm is along the neck and fixed on the trochanter. In other words, the extremes of this physical arm are the femur head and the trochanter. The hip biomechanical-load that makes the torque-magnitude is exerted over the head. Therefore, summing up all these causes, the pathological and biomechanical conditions become synergic in an elderly patient with osteoporosis, whose ligaments and muscles are also weak. When the patient moves abruptly or falls for any reason, the fracture could occur.

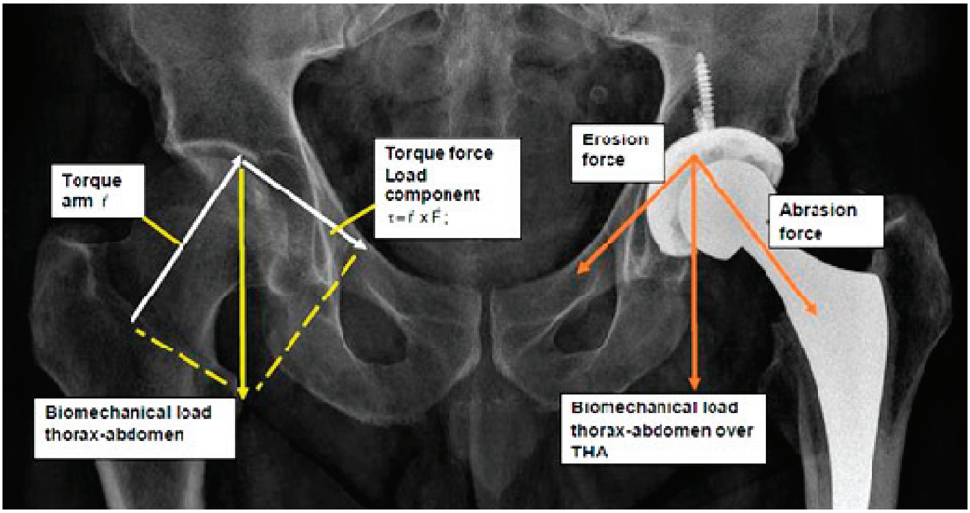

Figure 1. On the left, pictured inset, the mechanical torque sketch that could cause a femur neck fracture. Biomechanical torque τ and formulation inset. On the right, pictured inset, the biomechanical forces distribution that make wear and abrasion in the THA device (Google free images labeled and drawn by author).

In these clinical-surgical circumstances, when a THA is implanted, the medical device is subject to a number of biomechanical forces/parameters. These act on the THA material components and cause mainly wear by erosion and abrasion. The mathematical-physical modelling to determine/measure them precisely is essential, both in vitro (at laboratory with a number of apparatus) and/or in vivo (through several imaging with/without computational geometry methods).

Grosso modo, for in vitro, there are two types of methods, analytical and numerical. Analytical models could involve integral-differential calculus [13–16], and are usually based on these model variants. The numerical group involves finite element techniques, both linear and nonlinear. In these finite element models, the element wear can be formulated using Archard's variants [15,17]. A classical analytical method is based on modified Archard's model Equation (1), which is the focus of this study [1,14–16].

Analytical models could be linear and nonlinear [1,14–16]. The linear models integrate the hardness within the K parameter. In this study, hardness is considered as an important separated parameter for optimization [1,2,14–16]. In the literature, some authors begin developing the nonlinear model through integral-differential calculus and perform finite element calculations [15]. Figure 1 shows a sketch of biomechanical theoretical base for the analytic model. The principal cause of wear in THA is abrasive wear type or three body abrasive wear [14,16].

2. Materials and Methods

Materials selected for dual optimization are cast Co-Cr alloy and titanium. There are several generations of titanium varieties [2,7,8]. Modern beta titanium alloys have metastable physical-chemical useful properties for THA. Their physical characteristics are detailed in Table 1. The material and corresponding experimental in vitro erosion data in this study were taken from the literature [3,9]. However, for THA ceramic modelling optimization in previous studies [1], other authors' and publications were considered [17–20]. The in vitro wear rates published in [3] constitute acceptable approximated data for model optimization intervals, although in this study the interval-standards published in [9] were implemented in programming. The criteria for testing measurements/units and experimental apparatus varies in the literature [3,9,17–21]. For instance, in [19], the depth of wear for a unit of sliding distance is selected. Other authors [20] chose the criteria in mm^3/year, (volumetric wear), or mm/year (linear wear). This research selection is mainly practical for getting precise optimization. In this line, if experimental wear is measured in mm^3, it is straightforward guessed that K in Equation (1) becomes adimensional. In all cases, units are adapted on Section 2.1 criteria. Mathematical method(s) and algorithms are explained in Section 2.2. The software implemented constitutes an improvement stage from a former ceramic and metal THA modelling contribution and related publications whose programming tools are similar [1,2,6,22–25].

Table 1. Computational implementation numerical data and intervals for optimization.

Programming Numerical Data		
Material	**Hardness (Hv) and Histocompatibility**	**Head Diameter (mm)**
Cast Co-Cr alloy	300 Average/good	28 [22, 28]
Titanium alloy	362 (approx)/excellent	28 [22, 28]
Optimization Data Intervals		
Hardness (GPa)	[2.7, 4.0]	
Experimental Erosion (mm^3/Mc)	[0.01, 1.8]	
Complementary Data	ElasticityModulus and Fracture Thoughness are useful for other type of calculations. The standard femoral head used diameter is 28 mm. Cast Co-Cr alloy hardness varies in literature. There are a large number of Titanium alloys available with closely hardness.	

2.1. Material and Computational Data

Table 1 shows the material selection data and computational intervals. Provided the units are set in mm, mm^3, kg, and s, the standard K parameter of the model becomes adimensional [1,2]. This constitutes an advantage for simplicity/easy calculations with experimental data in vitro.

The hardness of cast Co-Cr alloy is 300 Hv (approximately 3.00 GPa); it is an average value since there are several types of this material. Titanium materials are also manufactured in a number of variant chemical compositions. The average is 362 Hv (approximately 3.62 GPa). The head diameter of the THA is selected as the most frequent standard of 28 mm. Therefore, to make a suitable range of hardness optimization, these hardness values are slightly extrapolated to enlarge the interval extremes, that is, in GPa [2.7, 4.0]. Experimental values are taken from published data [3], and the same technique as hardness interval construction was performed. That is, [0.01, 1.8] mm^3 per Mc. Additional material parameters such as elasticity modulus and fracture toughness are important to characterize the material, but not useful for this type of optimization.

2.2. Optimization Algorithms and Programming-Software Design

The algorithms implemented are based on classical Archard's model [1,2,14,16], but with vector-matrix and units modifications [1,2]. A variant from this model with evolution algorithms was developed in previous contributions [1,2,24]. The classical equation for wear optimization of hip implants reads,

$$W = K \frac{L \times X}{H} ; \tag{1}$$

where K is the wear constant specific for each material, L is the biomechanical load (N, passed here to kg and mm), X is the sliding distance of the acetabular semi-sphere of the implant (mm), W is the wear (mm^3), and H is the hardness of the implant material (MPa, here it is used always as kg and mm). X is measured as the number of rotations of the implant multiplied by half the distance of its circular-spherical length. However, in this study it is better approximated according to human biomechanics and kinesiology. The average rotation of femur head cannot reach 180° at any biomechanical movement in common patients. This is valid for flexion, extension, flexion-rotation, extension-rotation, abduction, adduction, and external/internal rotation [3,19,20]. For the program settings, one cycle is taken as the length corresponding to the maximum kinesiologic rotation angle. The maximum femur rotation angle value is 145° in flexion. In the software, this magnitude is implemented.

A Mc is defined as the length of the femur head circumference during the hip articulation movement (X). That is the standard for many in vitro experimental studies. If at the laboratory the erosion for 1 Mc is determined, then several million cycles (Mcs) can be approximated with the model. Arithmetically, a Mc (a million cycles of femur head during movement) of rotation length is calculated: circumference implant-head radius R by π for a factor of angle of 145° and by 10^6. Therefore, the erosion in vitro data resulted from this optimization always has to be considered as the maximum possible. Figure 2 shows the biomechanical kinetics for rotation angles implemented in programming. Number of rotations also depends on the daily physical activity of the patient, age, race, genetic heritage, associated diseases, country, sport habits, profession, climate, physical-activity culture, etc.

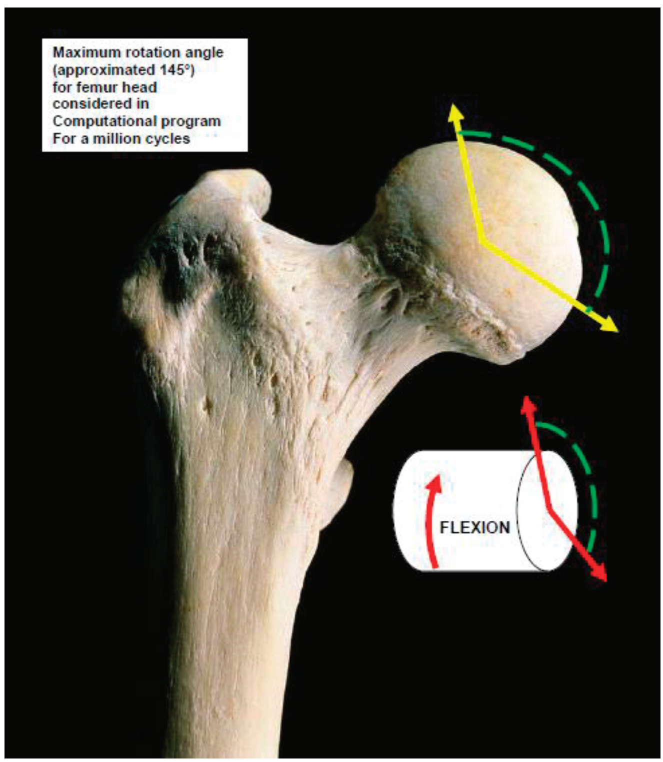

Figure 2. Sketch of kinetics rotation angles implemented in program (Google free images labeled and drawn by author).

The load magnitude to be implemented is rather difficult because usually the load is divided in X, Y, Z components [25,26]. Average values and/or forces resultant values are taken. For nonlinear optimization, the average values will be implemented in the program [1,2,26]. In this study, a load of around 200% of body weight (200%BW) is applied for optimization constraints, according to the most usual values of literature [2,3,19,20,26,27]. Constraints for load are set from a 50 kg patient to a 80 kg patient. Fifty kilograms corresponds, for example, to the body weight of elderly women, who present a high incidence/prevalence of femur head fractures.

Model (1) is also used in integral form for finite elements techniques in hip implants. K is a parameter, although in previous contributions, [1,2] this algorithm was implemented for more parameters, such as optimal hardness or number of rotations.

The algorithm is based on vectorial and matrix calculus. These vectors and matrices are set into the software. The parameters such as hardness, load, and experimental wear are set as vectors of 10^3 elements within the data interval set. The mathematical operations of these vectors when setting into the model require a careful and precise method to obtain the objective function ready for the subroutine. Least squares optimization method was widely applied in previous studies [2,18,22,24,26–34].

Least squares method with L_2 norm is widely used and has the advantage that the OF is always positive. For setting the inverse optimization problem, this technique can be considered acceptable [30–33].

Therefore, the least squares OF with L_2 norm that is used, [1], without fixed constraints reads,

Minimize,

$$\|\vec{W} - \vec{K}\frac{\vec{L} \times \vec{X}}{\vec{H}}\|_2^2 \cong 0;$$

subject to (generically),

$$\begin{bmatrix} a \\ b \\ c \\ d \\ e \end{bmatrix} \leq \begin{bmatrix} |K_i| \\ |L_i| \\ |X_i| \\ |H_i| \\ |W_i| \end{bmatrix} \leq \begin{bmatrix} a_1 \\ b_1 \\ c_1 \\ d_1 \\ e_1 \end{bmatrix}; \quad (2)$$

The software and mathematical methods of this contribution constitute both an improved evolution and completely different programs from previous publications [2,22,25,34–36] with Matlab and L_2 norm. 2D, Figures 3 and 4, and 3D graphical subroutines have been used in previous contributions [31,33]. In [37], biomechanical data was used to design software. Fortran 90 [22,32] was used to check/validate the numerical precision of the results. Freemat [18,22,32] was used to verify 3D Interior Optimization, as shown in Figures 5–9. The variations/ improvements are usage of 2D Graphical Optimization and 3D Interior Optimization methods [2,22,35,36]. The software is different in every case. The least-squares OF inverse algorithm [1,2,22,24,32,34] implemented reads,

$$\begin{aligned}
&\text{minimize,}\\
&\| F\left(\vec{W}, \vec{K}, \vec{H}, \vec{L}, \vec{X}\right)\|_2^2 \cong \ldots\\
&\ldots \cong \sum_{i=1}^{i=N}\sum_{j=1}^{j=N}\ldots\\
&\ldots\sum_{k=1}^{k=N}\left(F_{ijk}\left(W_{ijk}, K_{ijk}, H_{ijk}, L_{ijk}, X_{ijk}\right)^2 + \ldots\right.\\
&\ldots + F_N(W_{N,N,N}, K_{N,N,N}, H_{N,N,N}, L_{N,N,N}, X_{N,N,N})^2);\\
&\text{subject generically to,}\\
&\begin{bmatrix} a \\ b \\ c \\ d \\ e \end{bmatrix} \leq \begin{bmatrix} |K_i| \\ |L_i| \\ |X_i| \\ |H_i| \\ |W_i| \end{bmatrix} \leq \begin{bmatrix} a_1 \\ b_1 \\ c_1 \\ d_1 \\ e_1 \end{bmatrix};
\end{aligned} \quad (3)$$

K is the principal variable for optimization. The reason is that with a multiobjective K parameter it is possible to carry out in vitro simulations in the materials selection process. The hardness for simulations in vitro, within the optimization hardness interval, could, therefore, be different than titanium and/or cast Co-Cr alloy [6]. Constraints are selected as follows,

$$\begin{aligned}
&\text{minimize OF, subject to,}\\
&N = 2 \times 10^6,\\
&\forall W \in \vec{W}, H \in \vec{H}, L \in \vec{L}, X \in \vec{X},\\
&0.01 \le |W| \le 1.8 \quad mm^3,\\
&2.7 \times 10^6 \le |H| \le 4.0 \times 10^6\,\text{kg, mm};\\
&7.5 \times 10^4 \times 9.8066 \le |L| \le 2.0 \times 10^5 \times 9.8066\,(200\%\,\text{BW});\\
&\|\vec{X}\| = \pi \times 28 \times (145 \times 10^6)/180\,(1\text{ Million cycles});
\end{aligned} \tag{4}$$

Provided this OF and constraints, the running program time resulted in between 2–8 min, with a standard current microprocessor and pc memory. 3D Interior Optimization takes a longer time because the number of nested arrays and patterns is higher than 2D Graphical Optimization. Scale factors are essential in both types of codes for sharp visualization [1,2,22,24,32].

Figures 3 and 4 show flowcharts for 2D Graphical Optimization and 3D Interior Optimization software design. Both programs demand a high level of precision and systematic consistency. The 2D Graphical Optimization program has several variants corresponding to the choice of the selected parameter for optimization, as visualized on the graph.

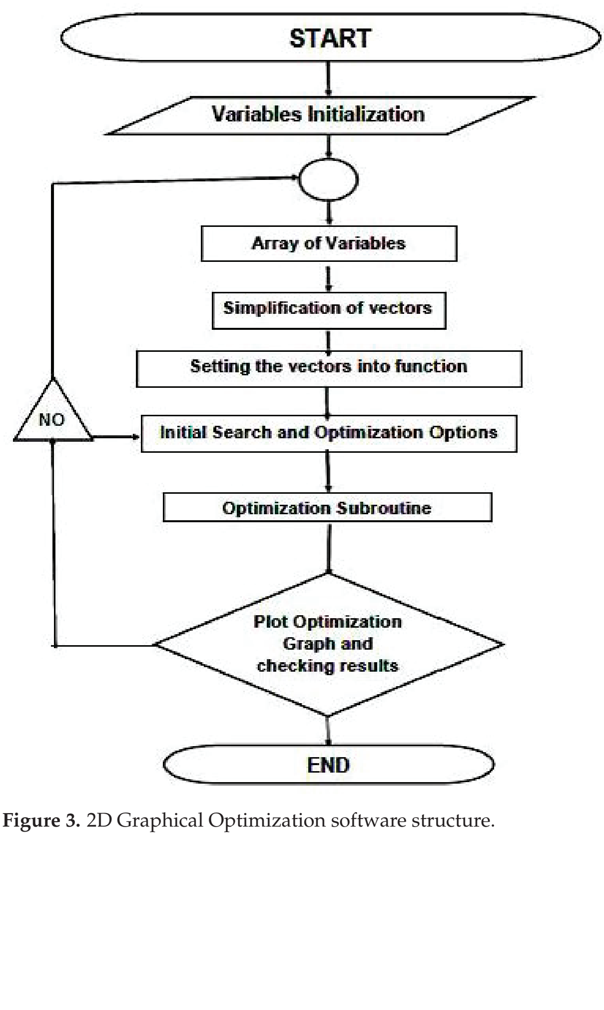

Figure 3. 2D Graphical Optimization software structure.

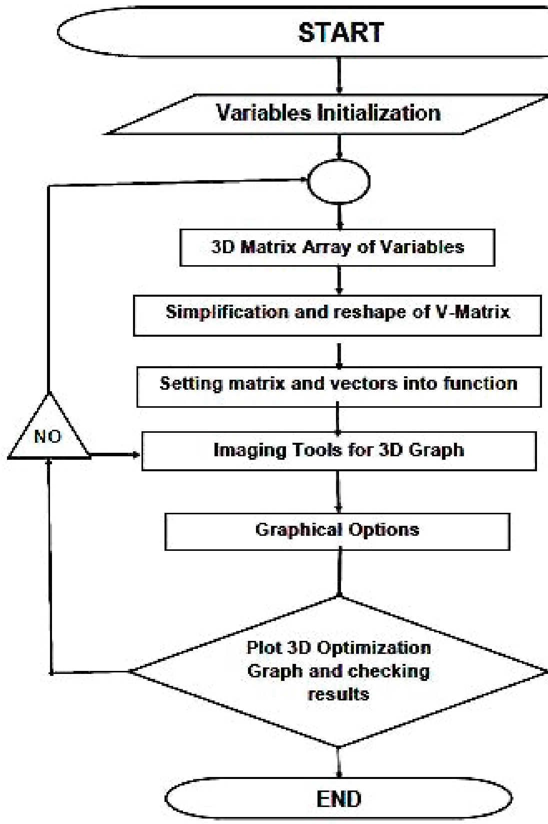

Figure 4. 3D Interior Optimization software structure.

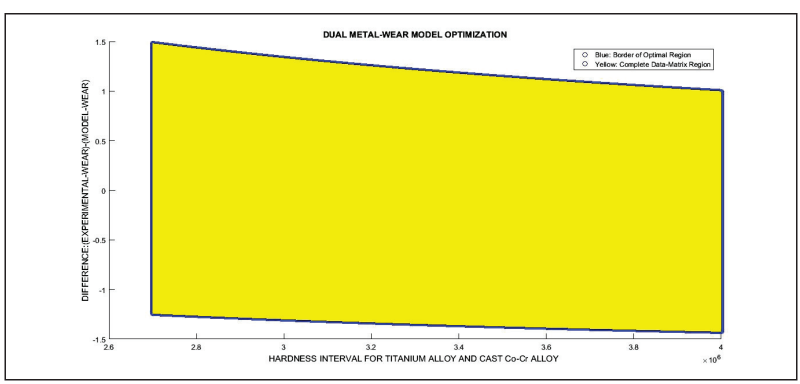

Figure 5. Optimization region and the decrease of erosion when hardness increases, and the difference between experimental values and model figures.

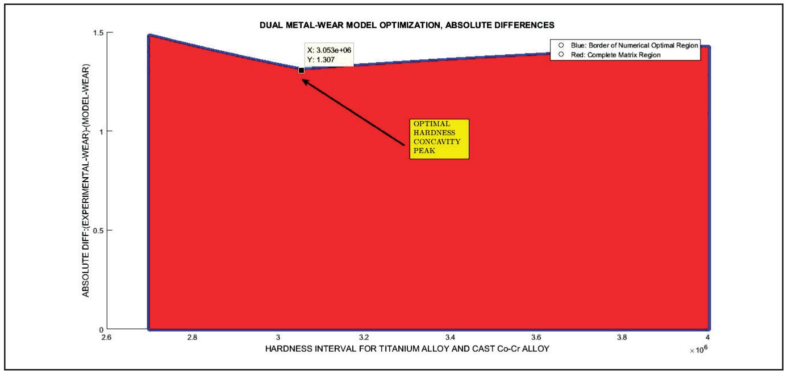

Figure 6. Optimal hardness obtained verification with 2D Graphical Optimization. Numerical value can be obtained both with software and graphics.

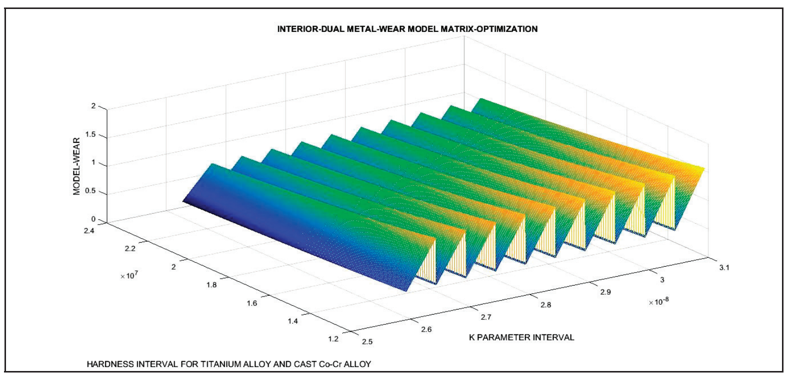

Figure 7. The 3D Interior Optimization matrix image with 10^5 elements. It proves that erosion is higher when hardness is lower and load is higher. The matrix has 10^5 elements and was set with a K optimal interval that was obtained with a 2D optimization algorithm. The program was rather difficult with several long nested patterns.

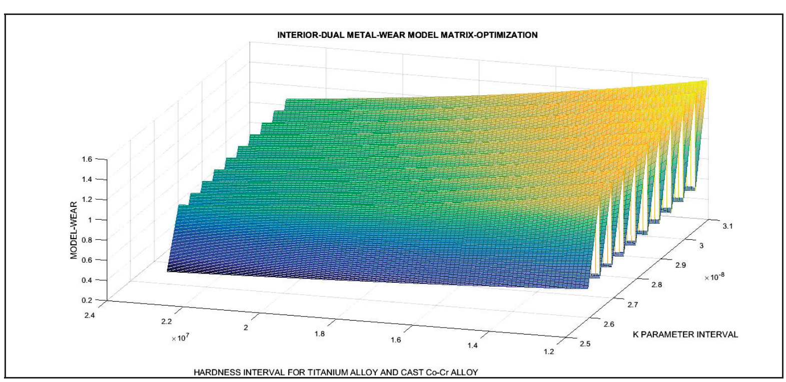

Figure 8. Lateral view of the 3D Interior Optimization matrix image with 10^5 elements. K optimal value is verified. It is visualized clearer that erosion is higher when hardness is lower and load is higher.

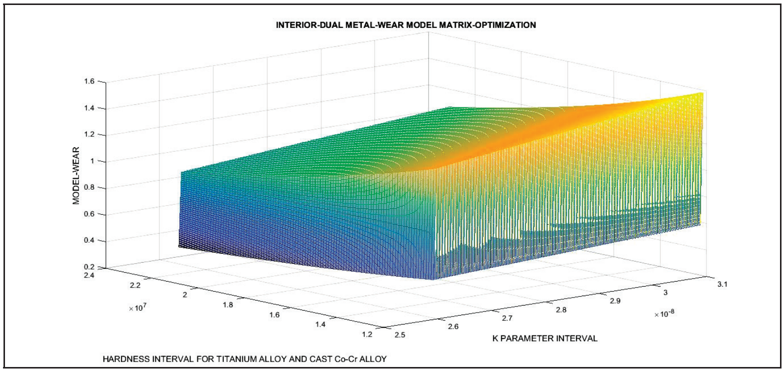

Figure 9. The 3D Interior Optimization matrix image with 10^6 elements. It proves even better that erosion is higher when hardness is lower and load is higher. The running time of this program is longer as the matrix has 10^6 elements. K optimal value is verified.

3. Results

The numerical results are obtained both from the optimization algorithm program numerical output and 2D Graphical and Interior Optimization charts; Table 2 shows all the numbers. The first figures that are obtained are the optimal K (local minimum) and the residual. With these values, the search for optimal hardness commences. This numerical tentative exploration is firstly done by using the Graphical Optimization plots—Figures 4 and 5. When plotting hardness interval versus absolute difference between model and experimental results, the concavity shows the optimal harness value with a cursor, as shown in Figure 6.

Table 2. Summary of numerical results.

Dual 2D Optimization Results and 3D Interior Optimization Results		
Material	**Optimal K Adimensional**	**Optimal Hardness (kg, mm)**
Cast Co-Cr alloy	28.93×10^{-9} (truncated)	3.05×10^{6} (truncated)
Titanium		
Residual for Optimal K	660.44×10^{3} (truncated)	
3D Interior Optimization Results		
3D matrix Program	Validation of K optimal adimensional parameter. In chart. Validation of erosion rises when Hardness decreases	

Once the optimal K and hardness are obtained, the 3D Interior Optimization process starts. Around the K optimal value, a wide interval is set on one axis. The other axis has the dual hardness interval. The Z axis shows the model wear. These 3D plot patterns are designed firstly with a 3D array (10^5 and 10^6 element matrices). These 3D volume matrices contain the elements L, H, and K. The plotting result is a 3D Graphical Optimization chart that verifies the optimal K value, since it is around the K optimal value. It is also clear that the erosion is higher at lower values of hardness, and those stair intervals correspond to the increasing loads for every K sub-interval of the array-matrix, as shown in Figures 7–9. When doing a 10^6 array-matrix, the plot results as a solid block that shows the increased erosion when hardness decreases.

3.1. Optimization Numerical Results

The numerical results are presented in Table 2 and can be read from graphics with Matlab. Graphics software was designed to show the local minimum as a function of several parameters. In Table 2, the dual nonlinear optimization for cast Co-Cr alloy and titanium is shown. The optimal K value obtained is 28.9295×10^{-9} with residual 660.4426×10^3. The optimal hardness obtained is 3.054×10^6. Figures 4 and 5 show the model 2D Graphical Optimization. The curves and areas correspond to the model objective function (Y axis) related to parameter values (X axis). Nonlinear dual 2D optimization matrix was set with 2 million functions. Running time was about 2–8 min to obtain local minima and graphics. The 2D surfaces obtained are filled with all the OF values for 2 million functions. As it occurred for THA ceramic modelling optimization [1], the exclusive existence of local minima is demonstrated. Residuals are low considering the 2 million OFs of the optimization matrix. 3D Interior Optimization graphs are shown in Figures 6–8. These prove the consistency of 2D Graphical and Numerical Optimization. Freemat [22,24] was used to verify 3D graphics and Fortran [5,24] for all numerical results. The Freemat images for 3D Interior Optimization are high quality.

3.2. 2D Optimization Results

The first optimization program has two parts. The first one is related to numerical results for K and optimal hardness. The second is the plotting of 2D Graphical Optimization. Table 1 details numerical results. Figures 5 and 6 show the 2D Graphical Optimization results for about 2×10^6 functions. Figure 5 demonstrates the optimization region and the decrease of erosion when hardness increases and the difference between experimental values and model figures. Figure 6 shows the optimal hardness obtained verification with 2D Graphical Optimization. The optimal K value obtained is 28.9295×10^{-9} with residual 660.4426×10^3. The optimal hardness obtained is 3.054×10^6. All numerical values are expressed in mm, mm^3, and kg. The K-metal magnitude results are higher than K-ceramic standard parameters for ceramic THA optimization [1,2].

3.3. 3D Optimization Results

Second optimization program(s) are based on nested arrays and a 3D volume-matrix with 10^5 elements (Figures 7 and 8, first program) and 10^6 elements (Figure 9, second program). The X axis shows a K interval around the optimal value obtained with the optimization program. The Y axis shows the hardness interval. All numerical values are expressed in mm, mm^3, and kg. The software design was rather complicated [1,2,22,24].

3.4. Optimization Numerical Results Verification

The numerical results verification can be checked in two ways. The first one is the 2D and 3D graphics parameters and intervals that provide numerical data distribution. The second is, for instance, to check whether the model optimal values are within the experimental interval. Hence, to verify the numerical results, the optimal values are implemented in the model as follows,

$$\begin{aligned} &\left| \mathrm{K(optimal)} \times \frac{\mathrm{Load\ (average)} \times \mathrm{Mc}}{\mathrm{Hardness\ (optimal)}} \right| \\ &= 28.93 \times 10^{-9} \times \frac{1.10 \times 10^6 \times \mathrm{Mc}}{3.05 \times 10^6} \\ &= 0.7393\,\mathrm{mm}^3 \in [0.01\,,\,1.8]; \end{aligned} \tag{5}$$

This was verified, since 0.7393 mm^3 belongs to the experimental interval [0.01, 1.8], approximately at its middle values. This implies that the theoretical model optimization is acceptable and matches the experimental in vitro laboratory measurements.

4. Discussion and Conclusions

An inverse dual optimization study was presented with an improved classical wear model and an original computational algorithm. The model was applied on material wear for metal THA. The selected materials were titanium and cast Co-Cr alloy. The software implemented for the algorithm [1,2] resulted in an acceptable standard K parameter and optimal hardness for the model. It is designed based on previous contributions [38–40], and THA/anatomical-physiological contributions [6,41]. The K parameter and optimal hardness can be used for any material wear prediction within the interval model whose parameters were computationally chosen. From a former contribution using this model, the obtained K-metal magnitude is higher compared to K-metal standard parameter [1,2]. Residuals in optimization performance are acceptable. The graphs presented resulted in being sharp with good magnitude visualization. The running time for programs was from 2 to 8 min. 2D Graphical Optimization graphs show the erosion distribution related to hardness. That is useful for wear magnitude prediction when in vitro experiments are carried out. The comparative study with previous research, namely THA erosion wear with the same model, confirms the optimal K figure of this study. The main reason is that the K order of magnitude, in ceramic one order lower, matches the in vitro experimental data with the model. 3D Graphical Optimization gives a range of K values that are also acceptable for wear at the hardness interval with low error dispersion.

The objective of the study was to obtain standard parameters for these two common metal materials in THA. The utility of the results is mainly focused on extrapolated-simulations/predictions of erosion rates for in vitro THA studies. Other variant materials within the selected interval ranges can be implemented in the model whose optimal parameters are determined. Improvements in algorithms, software, and model design are feasible from these findings. The contribution of these results in predictive wear methods is focused on in vitro experimental-computational erosion determinations. This means that the obtained K and hardness values for this model could be used as a numerical exact/approximated reference to get tentative data when planning an experiment. A useful, complementary advantage of the algorithm-model is the setting of K as an adimensional model-constant. That makes the experimental work easier with the units implemented into the model.

In brief, an accurate and efficacious dual optimization to obtain functional modelling parameters in metal THA erosion was presented. Applications in Medical Physics come from all these biotribological modelling improvements.

5. Scientific Ethics Standards

2D/3D Graphical-Optimization Methods were created by Dr Francisco Casesnoves on December 2016, and Interior Optimization Methods in 2019. This software was originally developed by the author. This article uses information from previous papers, whose inclusion is essential to make the contribution understandable. The nonlinear optimization software was improved from previous contributions in subroutines modifications, patterns, loops, graphics, and optimal visualization. This study was carried out according to the European Union Technology and Science Ethics. Reference, 'European Textbook on Ethics in Research'. European Commission, Directorate-General for Research. Unit L3. Governance and Ethics. European Research Area. Science and Society. EUR 24452 EN [42,43]. And based on The European Code of Conduct for Research Integrity. Revised Edition. ALLEA. 2017.y. Revised Edition. ALLEA. 2017. This research was completely done by the author: The computational-software, calculations, images, mathematical propositions and statements, reference citations, and text are all original from the author. When anything was taken from a source (Figures 1 and 2 free Google Images drawn and modified by Author), it was adequately recognized. Ideas from previous publications were emphasized in the aim of clarification [42,43].

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standards

Review

Explore3DM—A Directory and More for 3D Metrology

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Abstract: Explore3DM will be an online resource to explore the diverse interests behind three-dimensional measurement and three-dimensional metrology (3DM). The motivation has been the development of large-volume and portable 3D methods and systems for applications in manufacturing, an activity which has been growing for the past 40 years. However, the measurement spectrum in Explore3DM will be wider and include, for example, as-built process plant at the large-object end and X-Ray CT inspection at the small-object end. This wider spectrum will support cross-sector research at University College London (UCL) to transfer 3DM developments from one sector to another. Initially, Explore3DM will have a core directory incorporating systems manufacturers, service suppliers, research groups and disseminators of metrology knowledge. Mechanisms for solving end users' measurement tasks will add to further growth of 3DM. The resource is intended to be free to use and the directory free to join at a basic level. Premium directory sponsorship by commercial companies is expected to provide revenue to sustain and develop the resource and support 3DM development. With regard to standards, LVM and PCM systems and techniques can be difficult to assess with a standardized approach because of the highly flexible ways they can be applied. However, some standards have been developed and there is scope for more, for example in the terminology used. A dictionary will be a component of Explore3DM's future knowledge base. By presenting a first version in a centralized resource, standardized terminology will be encouraged.

Keywords: 3D metrology; large-volume metrology; portable coordinate metrology; photogrammetry

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1. Introduction

In the past 40 years, Large-Volume Metrology (LVM) and Portable Coordinate Measurement (PCM) have grown significantly with some hundreds of systems manufacturers and service providers now in operation as a result. The technologies have been developed to provide on-site measurement, where the measuring device is brought to an object's manufacturing location. Here, it is possible to support the manufacture and assembly of large objects, such as cars, aircraft and ships, or tasks, such as 3D deformation measurement at various scales.

Technologies for portable 3D metrology have significant origins in photogrammetry and surveying, in its most accurate form known as geodesy. Their use is long established in fields such as map-making and construction, where the tools must be transportable to the locations of interest. Photogrammetry has been further developed, for example in conjunction with projected patterns to create surface scanning systems [1]. These older technologies have been complemented by more recent developments, such as the laser tracker [2] and articulated measurement arm [3]. There is now a wide range of flexible 3D measuring technologies applicable to many manufacturing situations.

However, it is essential to take a wider view of 3D measurement. Users requiring portable 3D may also make extensive use of fixed-axis coordinate measurement and should understand their relative differences, strengths and operational characteristics. The mostly optical techniques of portable 3D can measure surfaces, not what lies beneath them. To measure sub-surface form, X-ray computed tomography could be a likely option. Optical systems delivering 10s of micrometers may work more efficiently in conjunction with mobile platforms located to centimeter accuracy by ultra-wideband (UWB) indoor location systems. A smartphone with appropriate software might quickly generate a 3D model of a space where several robot measuring cells are to be located.

Here are some of the related technologies relevant to a comprehensive understanding of 3D measurement and 3D metrology (3DM):

- **Industrial photogrammetry and surveying** As these technologies are the origin of many 3D metrology solutions, it is not surprising that they have continuing relevance, for example in the as-built modeling of the complex pipework in process plants or deformation monitoring of a bridge as traffic flows across it.
- **MoCap—Motion Capture** MoCap has application in medicine, e.g., for human gait analysis, and its use is particularly widespread in entertainment industries. Systems often use multi-camera, photogrammetric techniques to generate real-time modeling, typically of human movement. Accuracy may be lower than a photogrammetric system designed for metrology, but where speed and a turnkey system is required, MoCap may be a very appropriate solution.
- **Optical tooling** Optical tooling is an older technique where, for example, high-precision telescopes are used to align the bearings of a large driveshaft.
- **CMMs—Coordinate Measuring Machines** CMMs represent another older technology which maintains a strong manufacturing presence due to the high accuracies which they can deliver. They define three fixed axes in space, typically offering measuring volumes which accommodate object lengths of a few meters and are normally located in controlled environments to maintain their high accuracy. Objects to be measured must be brought to the CMM, a key difference with portable 3D.
- **X-Ray CT** X-Ray measurements can look below object surfaces and into object interiors, offering a 3D solution, which none of the above can offer.

Figure 1 [4–13] illustrates the spectrum of 3D measurement just described, centered on portable 3D technologies. One key element missing from this very positive development in measurement technology is an accessible, well-structured source of information which enables potential users to both understand and apply the relevant methods and systems to their own measurement challenges. A good understanding of how different techniques work, and are best applied, encourages good practice and delivers high-quality results. While automation and sophisticated algorithms have resulted in very efficient, self-contained commercial systems, on-going requirements to specify, for example, optimally configured networks of cameras or laser trackers still require an understanding of geometric principles and operational features. Even a fixed measurement system, such as a CMM, requires a complex calibration model to generate its high accuracy and good measurement strategies to further optimize results. Just two of the many good practice guides from the UK's National Physical Laboratory illustrate some of the above with GPG080 considering aspects of PCM and GPG041 looking at CMM measurement strategy [14].

One major effort in the process of disseminating relevant LVM and PCM knowledge was initiated and continued by the Coordinate Metrology Society (CMS), an internationally active organization based in the USA. The CMS started as a special interest group of the American Society for Photogrammetry and Remote Sensing (ASPRS) in 1984 and has subsequently developed into a learned society in its own right. Nearly 40 years on, the CMS delivers [15]:

- The annual Coordinate Metrology Society Conference (CMSC) held in the US
- The Journal of the CMSC with selected peer-reviewed papers from the conference
- A Certification Programme to give recognition to expert users of PCM systems
- 3DMU—the 3D Measurement U(niversity) offering online video training

Figure 1. Spectrum of 3D measurement.

The original motivation for the specialist group was to encourage industrial users of LVM and PCM systems to present their applications and thereby assist others to adopt portable 3D metrology solutions. The conference retains this practical approach to 3DM development and the concept has been emulated to a significant extent by the 3D Metrology Conference (3DMC) [16], a relatively new annual event currently being hosted in different European countries. Despite this comprehensive effort to disseminate 3DM knowledge, much more could still be done:

1. A knowledge base incorporating:
    - ○ A dictionary to provide quick access to relevant information
    - ○ A library of information to complement taught and remote training
2. Problem-solving mechanisms based on applications to expand the take-up of 3DM
3. A directory encompassing the entire 3DM community to bind the above together

The presentation here builds on the directory (3), which effectively provides a snapshot of the current extent and impact of 3DM. Problem solving using application examples (2) is a snapshot of the current range of tasks which 3DM addresses. When packaged together with background knowledge (1), a unique and accessible online tool is created.

2. Explore3DM—Background and Current Status

Independently, and in collaboration with University College London (UCL), previous attempts have been made to create some of the components mentioned above, as well as complete solutions:

- **2010: A library of LVM on Google Docs (no longer a facility offered by Google)**
- The author's structured arrangement of sample file extracts to act as a discussion tool.
- **2016: PCMA—an Academy of Portable Coordinate Measurement**
- The author's private Excel interface to a large collection of instructional and learning material.
- **2017: 3DIMPact-online.com (accessed on 18 August 2021) [17]** A demonstrator website from a 1-year project funded by UCL. The website requires access permission. The website demonstrates a directory, case studies and a knowledge base.
- **2018: Proposal to Engineering and Physical Sciences Research Council (EPSRC)** A £500K funding proposal by UCL to create Explore3DM, an international network for 3DM. The proposal was rejected in Jan. 2019.

- **2020: Unfunded partnership to initialize Explore3DM as a directory** A directory encompassing the entire 3DM community can also act as a network. Please contact the author if any of the above is of interest.

The 2020 partnership is between the author and Marked Improvement (MI), a web development company based in the UK and Spain [18]. MI has extensive experience in content management and the development of Learning Management Systems (LMS). The development will also link with the author's research work at UCL via a new Airbus/Royal Academy of Engineering Research Chair in Large-Volume Metrology. This chair has been awarded to Stuart Robson, UCL's Professor of Photogrammetry and Laser Scanning, and will be in operation from 2020 to 2026. This funded research not only supports specific Airbus interests in LVM but also the Academy's wider interests in expanding the impact of 3DM via mechanisms which include metrology training and cross-sector cooperation and information exchange, e.g., between construction and manufacturing.

The website is currently under construction and has the following key objectives:

- Bring together the 3DM technology users and technology suppliers
- Include the suppliers in a directory covering the entire 3DM community, i.e., systems manufacturers, service providers, researchers and knowledge disseminators
- Make it free to access, with free basic entries in the directory
- Create sustainable revenue from premium commercial company entries
- Use a significant percentage of net revenue to support the development of 3DM

Depending on available revenue, support for 3DM development will include:

- Contributing to the Academy's proposals for cross-sector knowledge transfer with activities such as:
    - Annual workshops
    - Metrology training for post-graduates and apprentices
    - Continuing Professional Development
    - Public engagement
- Increasing the impact of the 3D Metrology Conference
- Improving metrology connections between the UK and Brazil
    - Already established through private work and UCL travel grants
- Outreach to bring 3DM closer to university students and professional engineers

The following sections will discuss the first areas of active development, a directory and contact exchange, then scope for further development via an applications database and metrology knowledge base, including a dictionary.

3. The Directory of 3D Measurement and Metrology

Over a number of years, the author has collected website links to companies, organizations and groups which are directly or indirectly relevant to the 3D metrology spectrum (Figure 1). A number of these are now organized in an Excel file with a current classification allowing for:

1. Software for data capture, analysis and display (system manufacturers)
2. Hardware for data capture (system manufacturers)
3. Services
4. Resellers/distributors of software and hardware (sales, rentals and used equipment)
5. Innovation and development (including university research groups and similar)
6. Information and events (societies, conferences, publishers, etc.)
7. Training (providers of training courses)

These are further sub-classified with 651 active organizations currently listed and already imported into the Explore3DM website under construction. Recently collected links numbering in excess of 300 are also provisionally recorded in a Word file for further evaluation prior to addition to the new website's content manager. Before website launch, all sources will be contacted for approval.

Initiating the online resource with a directory has distinct advantages:

- Revenue-generating potential via support from listed commercial companies
- An initial mass of listed suppliers to attract a significant audience of end users

Note the current distributions by country of 544 systems and service providers, items 1–3 above, in Figures 2 and 3.

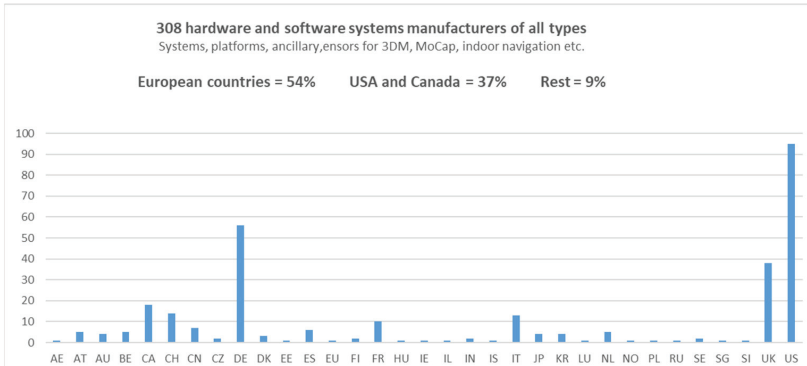


Figure 2. Distribution of systems manufacturers.

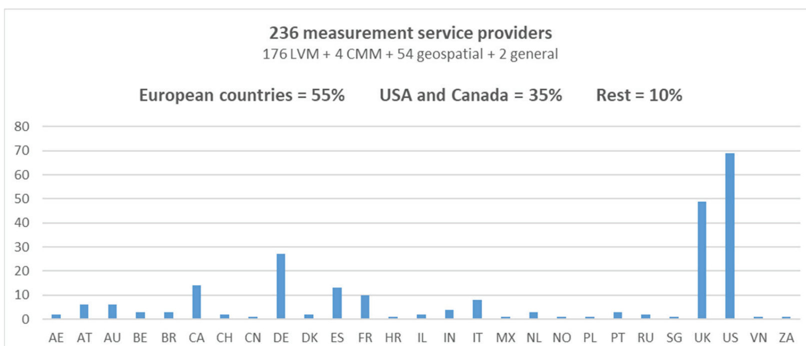


Figure 3. Distribution of service providers.

The directory will offer a free basic membership to any group or organization with relevance to the spectrum of 3D measurement and metrology. Revenue to maintain and develop the resource, and contribute to 3DM development, will be found from commercial companies willing to fund premium levels of membership. Research groups, non-profit organizations and key partners would have free premium membership in return for in-kind support, such as contributions to a knowledge base.

With suppliers and end users drawn to a contact point, there is scope to offer problem solutions.

4. Problem Solving

A technology directory would be particularly valuable if an end user could submit a query to it in the form "This is my measurement task. How do I solve it or develop a solution?". Then, the system should respond with, ideally, a highly focused answer of the form:

- "Systems of the following type are known to handle this task well . . . "
- "This international service provider in Brazil has related experience . . . "
- "These researchers in Germany have developed adaptable solutions . . . "

This would rapidly connect the user with potential sources of solution to the user's task. On one level, a user would solve a measurement challenge and suppliers would have an outlet for their goods, services or expertise. On another level, these interactions would extend the knowledge base of solutions, potentially with statistical indicators showing which are most successful. This, in turn, contributes to best practice, improved understanding and better quality control, which are key concepts for anyone concerned with standards.

4.1. Contact Exchange—Explore3DM's "Xchange"

The developers of Explore3DM will offer a contact eXchange (the Xchange), where users (clients) can post tasks and directory members (providers) can suggest relevant responses. This is illustrated in Figure 4.

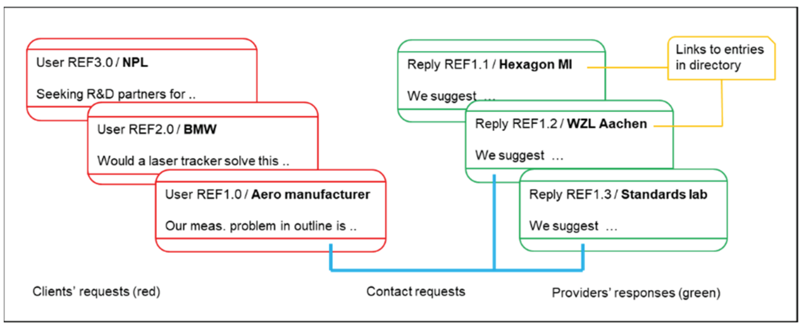


Figure 4. Solutions via the Xchange.

Not all tasks will be directly related to a measurement requirement. For example, there may be requests for partners in an upcoming research project, or advice in setting up a 3D measurement laboratory. However, many tasks will require solutions to a measurement challenge and a body of experts are an ideal source of well-considered responses. Clearly, the experts must be willing to respond to the tasks, and a classification of tasks could help direct only those of interest to particular experts.

Public viewing to some level of detail is proposed, so clients and providers may choose to name themselves generically and not with a company name, e.g., "aerospace" rather than "Boeing".

Clients might choose to make independent use of the responses or contact providers to take the discussion offline and to their own private level of detail. It is emphasized that this proposal is experimental and only through operation and modification can its effectiveness be determined.

4.2. Applications Database and Profile Matching

Another approach to problem solving is to build a database of known solutions which users can search for similarities to their own measurement tasks and evaluate sources of good matches.

The websites of many systems manufacturers and some service providers often provide free access to application information described as application reports, case studies, user stories or similar. The author has currently collected approximately 2000 of these documents. Thus far, some 750 can be accessed via an Excel file (Figure 5) and the remaining files will be added. The distribution of named users is shown in Figure 6.

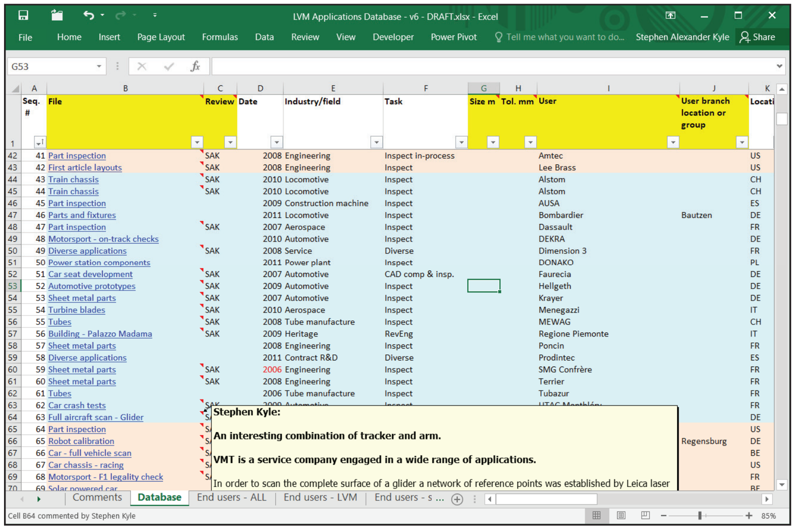


Figure 5. Author's Excel database of case studies.

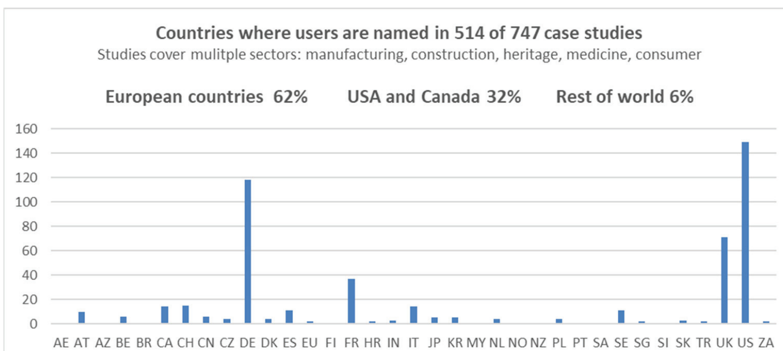


Figure 6. Distribution of named end users by country.

With this simple, in-house Excel database, it is possible to filter results by, say, company name, e.g., Siemens, and/or sector, e.g., aerospace, for a closer fit to a given measurement task. Users finding case studies similar to their own would then be able to approach the named source of the solution or look in more detail at the named technology in the solution. A potentially better search could be made if application reports contained minimum standardized information, such as:

- What is measured, i.e., an object descriptor such as "car door"
- The nature of the measurement task, e.g., surface damage or comparison with CAD
- The typical size or spread of the object or measured features, e.g., 1 m or 20 m
- The tolerance met by a given solution or required by a user, e.g., 0.2 mm at 1*

Optionally, more detail might be added, such as:

- System/surface interaction, e.g., targeted
- Object properties, e.g., static or deforming
- Task operation, e.g., manual or automated
- Environment, e.g., indoors or outdoors

The above information, when specified for a particular task, constitutes a task profile appropriate either to a user's specification or a source's knowledge of an actual application or a solution designed for a particular class of applications. The source's information then additionally provides:

- Solution used, e.g., tracker or photogrammetry
- Documentation, e.g., link to an application report

It is proposed to evaluate profile matching as another way of finding potential solutions to the measurement tasks facing end users. Here, users' required task profiles would be matched against known application profiles. The number of returned results would depend on an acceptable level of matching set by the user. Figure 7 illustrates the process.

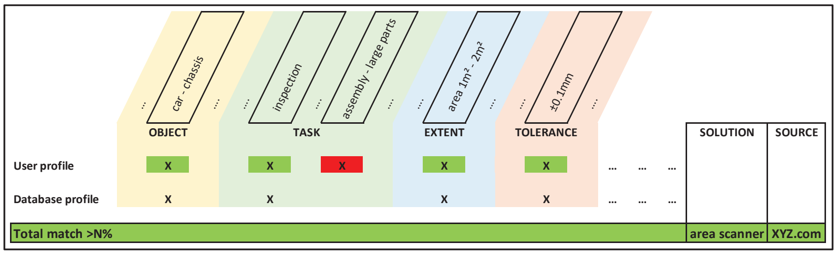


Figure 7. Task profile matching.

Note that the above process is initially based on data extracted from publicly accessible information but the additional supply of that information, such as an application report in PDF format, would require the agreement of the source.

5. Knowledge Base—A Dictionary and Library

Some basic introductory information would be highly appropriate as part of Explore3DM. It would help newcomers to find their way around the various technologies and applications of 3DM so that they could, at an early stage, make effective use of the directory and problem-solving tools on offer. It would also deliver a suitable response to the Royal Academy of Engineering's requirement for public engagement. Once in place, further information could be added to establish a multi-media library and comprehensive knowledgebase of 3DM.

Library information also has potential to connect with the directory, as another way of promoting resources which technology suppliers can provide.

Figure 1 is related to an existing multi-slideshow overview of 3DM, which contains a slide on calibration, adjustment and alignment, similar to Figure 8. Here, one image points to systems manufacturer FARO [7], showing a laser tracker solution, and one to research group i3mainz [19], showing a photogrammetric solution. The slide has been created by UCL's 3DIMPact Group [20]. Users of the directory might, for example, click on the logos for more information on the organizations behind the information.

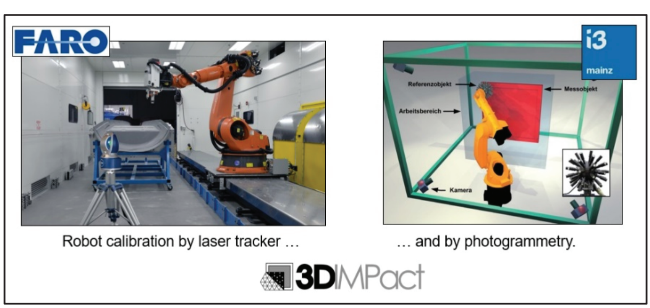
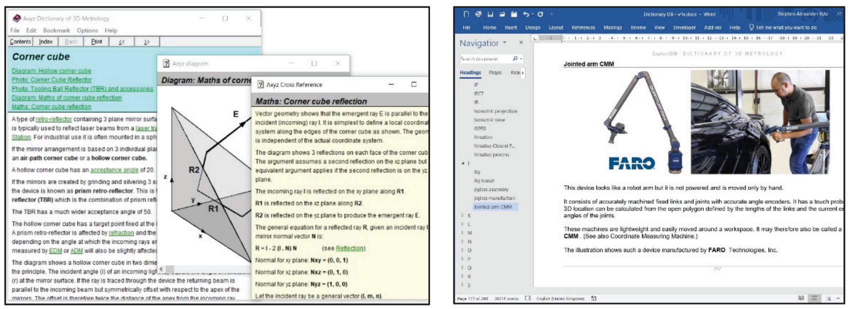


Figure 8. Illustrative introduction to calibration and alignment.

Dictionary—An Opportunity for Standardized Terminology

As an alternative to a structured presentation, a dictionary offers the ability to directly look up terms and, ideally, their context and connection to other terms.

The author's prototype dictionary illustrates some features of interest. Figure 9a shows an example from the Axyz Dictionary of 3D Metrology, created as a WinHELP file by the author in 2000 for Leica Geosystems. The example explains "corner cube" with optionally available additional information displayed in separate windows (diagram of the reflection process, mathematics of reflection). Figure 9b is a later Word version of the dictionary illustrating a definition of "jointed arm CMM" with illustrations from FARO, which could, again, link to the FARO entry in the directory.



(**a**) (**b**)

Figure 9. Prototype dictionary in two formats; (**a**) WinHELP file (2000), (**b**) WORD file (2021).

Explore3DM is not primarily about developing standards, but it can clearly act as a focal point for encouraging the use and further development of standards. One aspect of 3DM lacking in standardization is terminology in the proposed dictionary. Here, a few examples will highlight some areas where usage is inconsistent and alternative terms describe the same item. The examples all have relevance to 3DM, and thus, appear in the author's 1000-term draft dictionary.

- In English, should there be a preferred spelling option: coordinate or co-ordinate?
- Drones are useful mobile platforms in 3D measurement, even indoors. The term "drone" is in everyday use but is it an acceptable technical term or should we only use a term such as Unmanned Aerial Vehicle (UAV)? Or should that be UAS, where "S" is for system? Or both?
- Which term is preferable: "CMM arm" or "Articulated Arm Coordinate Measuring Machine (AACMM)" as used in the standard ASME B89.4.22?
- Are Laser Radar and LiDAR the same thing?
- Does Frequency Scanning Interferometry (FSI) do the same as "chirping" in Laser Radar, also called Coherent Laser Radar (CLR)? If so, is there an overlap in terminology which should be resolved or are different terms required?
- A "stereo camera" is sometimes identified as a "3D camera". However, the latter might be a range/imaging camera which operates in a different way from the dual-imaging stereo camera. Both would seem to deserve a separate definition in order to distinguish between them.
- There are manufacturers of "optical CMMs" which incorporate a moving probe or scanner, together with an "optical tracker" which has three cylindrical lenses fixed in a single housing. Each generates a line image of LED targets on the probe, locating them spatially by the intersection of three planes. Should this have a more specific name than "optical tracker", e.g., "triplanar camera" or "3-line imager"?

As a final example, it could be expected that angle conventions in 3D geometry are well established but usage can be mixed.

- The term "vertical angle" is sometimes used for an angle in the (nominally) vertical plane, which is zero when pointing not horizontally but along the zenith, which is vertically up. In this case, the author prefers the term "zenith angle", with "vertical angle" reserved for an angle which is zero when indicating a horizontal direction.
- There is a similar situation with horizontal angles where an angle in the XY plane zeroed in the X direction is then 90° on the Y axis, and hence, positive anticlockwise. However, this angle is often also named an "azimuth angle", which, in surveying and mapmaking, is an angle zeroed when pointing north and 90° when pointing east, and hence, positive clockwise.

This mixed terminology can be seen, for example, in [21], which is perfectly clear in its presentation but is given here as an example of mixed usage. Confusions arise, however, when presentations are not so clear, hence justifying some degree of standardization.

6. Cross-Sector Engagement in LVM

LVM and PCM incorporate highly scalable measurement techniques and are ideal for exploring and implementing cross-sector exchanges of 3D measurement and metrology solutions. This is an aspect to UCL's research work, which is funded by the Royal Academy of Engineering and which will benefit from the development of Explore3DM. Existing examples will illustrate the potential here. These examples show measurement at mixed scales and the application of closely related techniques in different sectors.

Very mixed scales are evident in particle accelerator alignment where beams of subatomic particles are guided on linear and circular paths, for example bringing opposing beams into collision in order to gain insights into the structure of matter. One of the new accelerators, the Brazilian Synchrotron Light Laboratory known as Sirius, is located in a circular tunnel about half a kilometer in circumference. Within this large civil engineering construction, magnets must be aligned to 10 s of micrometers in order to maintain and direct the particle beam. A measurement network covering the entire ring achieved submillimeter uncertainty, thus demonstrating alignment accuracies at construction scales. See the video by Geraissate, directly viewable on the 3DMC website or downloadable from the 3DMC archives [16]. A number of such accelerator alignment groups can be found in the directory.

The directory also lists service companies which offer both engineering surveying services, such as as-built modeling of process plant, together with industrial metrology services, such as precision alignment. The website of Heinz Meschke in Germany is a good illustration of this. See "Ingenieurvermessung" and "Industrievermessung" [22].

Finally, note how American company Capture3D reports on the use of system manufacturer GOM's 3D surface scanner, ATOS, for cultural heritage recording of a bronze sculpture [23] and for digitizing the mold of a protective mask [24]; heritage on the one hand, manufacturing on the other.

7. Further Information and Future Development

This review in the launch issue of "Standards" was based on an online presentation of the current status of Explore3DM delivered by the Midlands Centre for Data-Driven Metrology [25]. This center was launched in November 2020 and is a multi-site collaboration between the University of Nottingham, Loughborough University, and Coventry University.

With regard to future development, there are many opportunities to consider, some of which will not be apparent until Explore3DM is in operation. One area of particular interest relates to the applications database, a potential source of problem solutions. A first-stage development would be a standardized approach to defining task profiles in order to improve the search functionality. As this database expands, better matching techniques may be possible, e.g., using artificial intelligence to analyze the task database.

8. Conclusions

Explore3DM is a novel and developing resource which will initially deliver a comprehensive directory of 3D metrology suppliers and a contact exchange to help end users identify suppliers who can assist with their metrology tasks. In operation, it should support the development of 3D metrology by giving the entire 3D metrology community, both commercial and non-profit, a location to showcase their products, services and skills and make new connections.

As it develops, it will encourage good practice and, in some cases, standardization where there are current limitations.

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Article

Rating Potential Land Use Taking Ecosystem Service into Account—How to Manage Trade-Offs

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Abstract: Rating the potential land use for crop production and/or ranching is typically a process where production gains counterbalance environmental losses. Whereas the production gains are often easy to verify, the environmental losses may render visibility through the changes in the ecosystem service, such as water and habitat quality, carbon storage, etc., thus, leaving the decision maker with a multi-criteria problem. The present study demonstrates how partial-order methodology constitutes an advantageous tool for rating/ranking land use that takes trade-offs into account. It is demonstrated that not only the optimal choice of area, on an average basis, e.g., for crop production, is disclosed, but also the relative importance of the included indicators (production gains, ecosystem losses). A short introduction is given, applying data from a recent Chinese study looking for the optimal monoculture as a function of ecosystem tradeoffs. A more elaborate system applying data from the esgame was used, disclosing the most beneficial area for crop production and for ranching, as well as the relative indicators' importance. The study further demonstrates that a single composite indicator obtained by simple aggregation of indicator values as a ranking tool may lead to a result where gains are optimized; however, this comes at the expense of the environment.

Keywords: multi-criteria decision analyses; MCDA; partial ordering; Hasse diagrams partial ordering; average ranking; indicator importance

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1. Introduction

Decisions about land use are often based on a single assumption, i.e., maximizing the yield, of crops or cattle-based products. However, agriculture or ranching may pose significant, typically negative influences on ecosystem services such as water and habitat quality, carbon storage, and hunting and foraging. Thus, in order to optimally rate or rank land use, it is necessary to consider the "costs" of the changes in the ecosystem services (ESs). Typically, we face positive production outcomes and gains on the ESs, on one hand, and negative impacts and losses on the other. Thus, optimizing the land use will be the result of a trade-off analysis considering the difference indicators [1].

A multi-criteria system (MIS) considers both the outcome of the production and the influence on the ESs. Very often, such systems are analyzed by a simple, e.g., arithmetic aggregation of the single indicators (criteria) to one composite indicator that allows a strict linear ordering of the objects studied. However, such analyses may be subject to erroneous results and, thus, decisions due to compensation effects [2], i.e., where one high value may be compensated by other rather low values, without knowing the actual influence or importance of the single indicators. Hence, multi-criteria decision analyses (MCDAs) may advantageously be brought into play. MCDAs have previously been used in the study of ecosystem services [3–8]. These studies review or apply a variety of MCDA methods for trade-off analyses of ecosystem services. A joint trend is that the weights are introduced in an attempt to generate a composite indicator by aggregation (see, e.g., [7,8]) or comparing indicators pairwise, as proposed by Lee and Launtenbach [3]. In none of these studies do the applied methods bring all indicators simultaneously into play without pretreatment, as, e.g., weighted aggregation. Hence, MCDAtaking all indicators into account simultaneously may advantageously be brought into play.

To remedy this and to further add to the toolbox, the present study introduces a partial order methodology (cf., e.g., [9–17] as a method to analyze MISs, and it focuses on the tradeoffs between production outcome and changes in ecosystem services.

Partial ordering is an advantageous methodology for such studies as it considers all features (indicators) simultaneously without any pre-assumptions or pretreatments such as aggregation. As such, the analyses avoid potential problems such as compensation effects [2]. Thus, the influence/importance of the single indicators is immediately disclosed by partial order analyses, which may constitute important information for decision makers as they here suggested, e.g., that resources should be allocated for improvements of the system.

The overall objective of the study is to provide a simple MCDA, that is, a partial ordering methodology to analyze MISs, in this case trade-off issues in land use, by taking ecosystem services into account. The partial order methodology is briefly described in Section 2; however, references to the available literature for a deeper theoretical background and understanding of the techniques are provided. Hence, the analyses of trade-off issues will initially be illustrated by a simple exemplary case based on data from a recent Chinese study [18] (Section 3.1), followed by a more elaborate system applying data from the trade-off game [19,20] (Sections 3.2 and 3.3). Finally, Section 4 provides conclusions and some outlooks on how the methodology may be applied.

Why Partial Ordering

When an MIS is to be evaluated, multivariate statistical methods such as correlation or regression analyses and clustering techniques are of primary interest. In some studies, only a regression analysis is considered as a method for an evaluation of an MIS [21]. However, regression analyses need a model concept, e.g., whether a linear model is appropriate or not or whether a nonlinear fitting model appears as a more appropriate choice. To some degree, this is also the case for principal component analyses. In the case of cluster analysis, the answer needs a few more remarks. In addition to the technical problem of how to define distances among groups of objects (cf. [22,23]), cluster analyses have no evaluative background, as the clustering is a result of distance measures. Nevertheless, the method appears attractive, and attempts to infer a posteriori ranking perspectives have been reported (cf., e.g., [24]). Partial order methods have their own disadvantages, such as the loss of any metric. However, the evaluative aspect is its main advantage. The comparison of the objects of interest is carried out simultaneously for all indicators, without the need for any prior aggregation (details below). In summary, the application of partial order methodology, at least as an interim process before other tools will be applied, is emphasized.

Although partial ordering is a relatively new method, the methodology has been demonstrated to be valuable in a wide variety of disciplines (cf., e.g., [10,25–34])

2. Methodology

2.1. Partial Ordering—The Basics

The basis for partial ordering is the relation among the objects to be ordered. Formally, the only mathematical term in this context is the "$\leq$" relation (cf., e.g., [9–17]). The role of this relation is fixed up by following axioms [10]:

$$\text{Axiom 1:} \quad \text{Reflexivity:} \qquad x \in X\text{: } x \leq x \tag{1}$$

$$\text{Axiom 2:} \quad \text{Anti-symmetry:} \qquad x \leq y,\ y \leq x \text{ implies } y = x \tag{2}$$

$$\text{Axiom 3:} \quad \text{Transitivity:} \qquad x \leq y \text{ and } y \leq z \text{ implies } x \leq z \tag{3}$$

Reflexivity means that a given object can be compared with itself.

Anti-symmetry means that if both comparisons are valid, i.e., y is better than x and at the same time, x is better than y, then this axiom demands that x is identical with y. Instead, we accept equivalences.

Transitivity means that if the objects are characterized by properties which are at least ordinal scaled, then any measurable quantity such as height, length, price, etc. implies transitivity.

Hence, the "≤" relation is the basis for a comparison of objects and constitutes a graph, the so-called Hasse diagram (see below). Two objects relate to each other, i.e., are comparable if and only if the relation $x \leq y$ holds. Since a given object, x, is characterized by the a set of indicators $r_j(x)$, j = 1, ... , m, it can be compared to another object y, characterized by an identical set of indicators $r_j(y)$, if

$$r_i(x) \leq r_i(y) \text{ for all } i = 1, \ldots, m \quad (4)$$

which requires that at least one indicator value of object x must be lower and the remaining lower or at least equal to those of object y if a comparison should be established. If Equation (2) does not hold, the two objects will be incomparable (notation: $y \parallel x$). The two objects with all indicators that have identical values and are equal are denoted equivalent (notation: $x \sim y$); in ranking terms, this means that they will have the same.

Concepts of Partial Ordering

Given a partial order some concepts are of importance. Let us look at two objects, x and y, in the MIS.

1. Max(MIS): the set of objects of the MIS, where no other object y can be found with $y > x$. This is the set of maximal objects of a partially ordered set (poset). If x is the only maximal object, it is called the "greatest" object;
2. Min(MIS): the set of objects of the MIS, where no other object y can be found with $y < x$. This is the set of minimal objects of a poset. If x is the only minimal object, x is called the "least" object;
3. Iso(MIS): the set of elements of the MIS that at the same time are elements of Max(MIS) and Min(MIS). Such objects are called isolated objects. Within the context of a MIS the data values leading to objects that are not compared to any other object. These elements may be of special interest;
4. Chain: A subset of the MIS, where each object is mutually comparable with others;
5. Antichain: A subset the MIS, where each object is mutually incomparable with others;
6. Level: The subset of the MIS, where all objects have the same rank.

The construction of the system of levels taken from a poset is of special importance. Algorithmically, it is not the best way to follow the definition but to define an iterative procedure, as explained in Bruggemann and Patil [10]. By levels a weak order is defined. A weak order is an order, where equivalences are accepted. For example, the sequence $a < b = b = c < d < e = f$ is not an order, because there are equivalences, but it is a weak order. From a statistical point of view the fact of equivalences is considered as disadvantageous, because objects are insufficiently separated. Within the context of partial order, the level structure is often a first attempt to find a weak order for a given objects. Note, if the MIS is a chain, i.e., all objects of the MIS are mutually comparable, then each level consists of only one object and then the level structure defines an order.

For a deeper theoretical explanation of the methodology the above-mentioned references should be consulted.

2.2. The Hasse Diagram

Equation (1) is the basis for the Hasse diagram technique (HDT) [10,25]. Hasse diagrams are visual representation of the partial order. In the Hasse diagram comparable objects are connected by a sequence of lines [10,11,25,30,31]. Thus, sets of comparable objects, i.e., fulfilling Equation (1) are called chains that in the diagram are connected with lines, whereas sets of mutually incomparable objects, i.e., not fulfilling Equation (1) are called antichains.

In the diagram the single objects are positioned in levels, typically arranged from low to high (bottom to top in the diagram). A general rule is that objects are located a high in the diagram as possible. Thus, isolated objects, i.e., objects that are not comparable to any other objects, will by default be placed at the top level of the diagram. In the case of equivalent objects only one representative for each of the equivalent classes will be shown in the diagram.

The module mHDCl7_1 of the PyHasse software (vide infra) was used for the basic partial ordering calculations and the associated construction of the Hasse diagrams.

The Orientation

It is important to make sure that the orientation of the single indicators is identical, e.g., that high values correspond to "good", whereas low values correspond to "bad". In practice, this is carried out by multiplying indicator values by -1 in case where high and low values correspond to "bad" and "good", respectively (cf. Section 2.5). In the present study, the highest located object will be assigned rank 1 indicating the "best".

2.3. Average Ranking

Looking at the Hasse diagram, the level structure constitutes a first approximation to ordering/ranking. However, as all objects in a level automatically will be assigned identical ranks such an ordering will obviously cause many tied orders. Obviously, it is desirable with a degree of tiednes being as low as possible. Hence, ultimately a linear ordering of the single objects is desirable. However, when incomparable objects are included in the study, obviously this is not obtainable. Partial order methodology provides a weak order, where tied orders are not excluded by calculating the average order of the single objects as, e.g., described by Bruggemann and Carlsen [32], Bruggemann and Annoni [33] and Carlsen and Bruggemann [16].

This method is mainly a combinatorial exercise, and one is confronted with computational difficulties if the MIS is a large set (more than 50 objects). This difficulty triggered many mathematical approaches how to circumvent the computational problems. A relatively famous method is the Monte Carlo Markov chain method proposed by Bubley and Dyer [29]. A "quick and dirty" method is the concept of local partial order, proposed by Bruggemann et al. [34], where the basic idea is to check the order theoretical environment of each single object of the MIS. The crucial question is, how large must the environment be selected to obtain reliable results. Depending on the selection of the environment different Local Partial Order Models (LPOM) arises. In the present study, the LPOMext is selected, where not only the chains, encompassing object x are considered but also its incomparable objects U(x): = {y ∈ X, with y ‖ x} (for details, see [32]).

The LPOM methods were compared with the results of an exact method, based on lattice theory [35,36] with surprisingly good results. However, the method by lattice theory fails when the MIS is large.

The average rankings were calculated applying the LPOMext9_1 [32] module of the PyHasse software (vide infra).

2.4. Sensitivity-Indicator Importance

A Hasse diagram has a certain structure (cf. Section 3.2). Thus, levels, isolated objects, chains, etc., constitute the "structure" of the diagram and, thus, the partial order. The structure of a Hasse diagram, in turn, is important for an elucidation of the data and their interpretation. The obvious question is, how the single indicators would affect the structure.

The relative importance of the single indicators in play can be determined through a sensitivity analysis [37]. The basic idea is to construct partial ordered sets (posets) excluding the single indicators one at the time. Subsequently, the distances from these posets to the original poset are determined. The indicator, whose elimination from the original poset leads to the maximal distance to the original one, in other words causing the highest degree of changes in the Hasse diagram is important for the structure of the original partial order [16].

The sensitivity values were calculated by the sensitivity24_5 module of the PyHasse software (vide infra).

2.5. Indicators

The rating of land use, taking the ecosystem service into account, is based on an indicator describing the gains/outcomes by the agricultural or ranching activities and 4 indicators describing the influence on four ecosystem services, i.e., carbon storage, habitat and water quality and hunting and foraging, respectively (Table 1). Two sets of indicators, for agriculture and ranching, respectively, are used.

Table 1. Indicators applied.

Indicator	Notation	Explanation
Production	crop_ag/past_ps	Agriculture/Ranching
Ecosystem service	agcarb/pscarb	Carbon storage (Agriculture/Ranching)
Ecosystem service	aghq/pshq	Habitat Quality (Agriculture/Ranching)
Ecosystem service	agwq/pswq	Water Quality (Agriculture/Ranching)
Ecosystem service	agrec/psrec	Hunting and Foraging (Agriculture/Ranching)

2.6. Data

2.6.1. The Exemplary Case

The data applied for the Chinese study was adopted directly from the paper by Zou et al. [18] summarizing the relative ecosystem services (Table 2).

Table 2. The relative ecosystem services (RES) of the seven monoculture patterns.

RES	Provisioning	Regulating	Supporting	Cultural
Corn	0.021	0.052	0.154	0.252
Marigold	0.052	0.23	0.141	0.504
Orange	0.025	0.587	0.473	0.607
Pear	0.144	0.576	0.586	0.607
Peach	0.038	0.881	0.846	0.607
Apple	0.169	0.872	0.811	0.814
Pomegranate	0.955	0.508	0.678	0.814

2.6.2. The Esgame

The data for the esgame study was obtain from Lacayo [19] and esgame [20]. The raw data [19] were transformed to fit the esgame [20], i.e., a 27 $\times$ 28 grid of square pieces of land. For each of these grid points values of the above-mentioned indicators are calculated. The unit of the indicator values is identical for all indicators. In total 5 indicators (columns) and 756 grid points (rows) constitute the MIS (Figure 1). Two separate MIS were obtained: one based on agriculture, i.e., crop production and one based on ranching, respectively. The color coding disclosing the distribution of indicator values can be found at the esgame web site [20]. Due to the actual size of these two MIS the data are not included in the present paper but can be obtained from the author upon request.

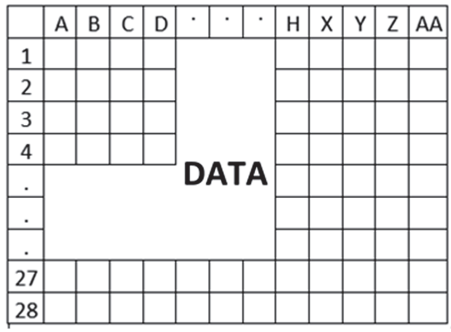

Figure 1. The area being investigated in 756 grid points.

As the production, i.e., crop production or ranching, in the esgame is considered to have a negative influence on the four ESs, the ESs indicators all have negative values in the MIS. Thus, for all indicators the term the higher the better prevails.

2.7. Software

All partial order analyses were carried out using the PyHasse software [26]. PyHasse is programmed using the interpreter language Python (version 2.6). Today, the software package contains more than one hundred specialized modules and is available upon request from the developer, R. Bruggemann (brg_home@web.de).

3. Results and Discussion

3.1. An Exemplary Case

To illustrate the partial ordering methodology, data from a recent Chinese study on trade-off analysis of ecosystem service [18] serve as an exemplary case. Thus, Zou et al. (2020) study the performance of ecosystem services (ESs), provisioning, regulating, supporting and cultural (cf. [18], Table 2) for seven typical monoculture patterns: corn, marigold, orange, pear, peach, apple, and pomegranate.

Based on the values given in Table 2, Zou et al. [18] draw a series of conclusions on the ecosystem services in the different monoculture patterns. However, they were not able to draw a final conclusion. Applying partial ordering, on the other hand, it is possible to obtain a more comprehensive picture, bringing all 4 ESs (the indicators) simultaneously into play. In Figure 2, the resulting Hasse diagram is shown.

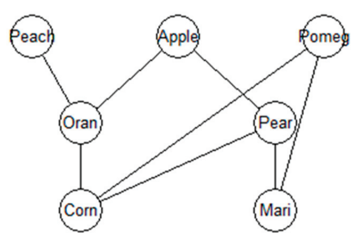

Figure 2. Hasse diagram visualizing the partial ordering of the seven monoculture pattens (cf. Zou et al. [18]).

It is immediately noted that peach, apple, and pomegranate appear at the top level of the diagram and as such is expected to be the most beneficial cultures in agreement with Zoe et al. [18]. Calculating the average ranking an even more decisive picture of the seven monocultures developed. Hence, we found apple from an ES point of view constitutes on an overall average basis as the preferable monoculture, the rating of the seven monocultures according to their qualifications to be Apple > Peach > Pomegranate > Pear > Orange > Marigold > Corn.

Looking at the relative importance of the single ESs it was disclosed that provisioning (0.500) > regulating (0.375), supporting (0.125) and cultural (0.000), i.e., that the cultural ES does not influence the partial ordering of the seven monoculture pattens, which with reference to the paper by Zou et al. [18] may not be surprising as this ES summarizes the "cost according to the equivalent education level of training" (cf. [18], Supplementary File S1).

3.2. The Esgame-Agriculture

As mentioned above, we are looking at a larger piece of land that has been divided into $27 \times 28 = 756$ square grid points (cf. Figure 1). Formally, the dimension of the land and grids are arbitrary. However, for clarity the single grids could be a $1000 \times 1000 = 1{,}000{,}000$ m^2, i.e., 100 hectar, which roughly corresponds to an average UK farm [38]. Each of the grid points are characterized by the 5 indicators crop_ag, agcarb, aghq, agwq and agrec (cf. Table 1). Quite a few of the grid points appear to be equivalent leaving 470 equivalent classes (cf. Section 2.2). Some of them are trivial classes, i.e., containing only one single grid point (called trivial equivalent classes), while other contain quite a few. Thus, the major non-trivial equivalent class contains all grid points where all indicator values equal zero. This class contains 274 objects. Further, 2 equivalent classes with 3 object and 8 with 2 objects, respectively, are present. The remaining 459 grid points are unique, i.e., trivial equivalent classes.

Overall, the 756 grid points can be divided into three main groups: (a) a group where all indicator values equal zero, meaning no production and thus no influence on the ESs, (b) a group where the combined data reflect that although we have a certain production the positive outcome is more than compensated by the negative influence on the ESs and (c) a group where the outcome of the production is higher than the negative impacts on the ESs. Obviously, the eventually preferred grid point is to be found within group c.

In contrast to the above exemplary case (Section 3.1) it has no meaning to graphically to visualize the Hasse diagram based on the agriculture MIS. Obviously, the information content of a Hasse diagram with 470 objects distributed over 12 levels is rather limited. Thus, in Table 3 a tabular version of the diagram is given.

Obviously, the above Hasse diagram only gives rather limited information concerning the actual ranking of the single grid points, as all objects in a given level are associated with the same rank. For a deeper insight into the mutual ranking of the grid points, the average ranking (cf. Section 2.3) is calculated. The top 10 grid points, i.e., the points that, on an average basis, appear as the most beneficial for agriculture (crop production) were found to be I11 > J11 > J10 > L13 > L8 > M13 > I12 > Y15 > N17 > K10, respectively (for notation cf. Figure 1). It can be noted that the top 9 grid points are found in level 12 of the Hasse diagram whereas the rank 10 grid point, K10, is located at level 11.

It is interesting to note that the grid point I11 on an average basis appears as the preferable, with an overall sum of the indicators equal to 675 count units. However, the maximum sum, which equals 750 count units, is, however, found for grid point M13, the value being obtain by a simple arithmetic aggregation of the five indicators. M13 is, on an average basis, found at rank 6. To explain why M13 should not be regarded as the top-ranked grid point, it is necessary to look at the indicator values for the two grid points (Table 4).

Table 3. Tabular version of the Hasse diagram corresponding to the agriculture grid. The naming of the single grid point corresponds to their location (cf. Figure 1).

Level	No of Grid Points	Grid Point (Equivalent Classes)
12	31	A1 C23 H20 I10 I11 I12 J10 J11 J17 K27 L8 L13 L27 M7 M9 M13 M26 N17 N21 N26 N27 S24 S26 S27 T17 T23 T24 T26 T27 U24 Y15
11	55	A21 B22 B23 D12 D15 E10 E11 E22 F10 F11 F22 G21 I17 I19 J20 J21 K7 K10 K20 K26 L7 L9 L12 L26 M10 M11 M20 M27 N18 N22 O17 O23 P14 P26 Q14 Q15 Q24 R2 R3 R15 R28 U8 U9 U17 V3 V7 W4 W6 X15 X22 Y9 Y10 Y14 Y16 Y18
10	70	D16 E12 E15 F12 F23 G22 H14 H19 I13 I18 J18 J22 J23 K6 K8 K11 K19 L4 L5 L6 L19 L20 M2 M6 M8 M12 M18 N2 N7 N16 N20 O2 O3 O6 O7 O9 O18 O22 O24 P6 P15 P23 P24 Q2 Q28 R14 R27 S12 S14 S17 S28 T12 T14 T18 U14 U16 U18 U21 U22 U23 V4 V22 W22 X9 X10 X16 X17 Y19 Z10 Z14
9	64	A18 A20 A22 B18 B19 C22 E13 E16 F13 G10 H12 H17 H18 H21 J16 J19 K9 K13 K16 K22 K23 K24 L3 L10 L11 L25 M17 M19 N10 N12 N13 N14 O27 P5 P25 Q13 Q23 R4 R16 R24 S2 S3 S11 S13 S23 T8 T11 T15 T16 T21 T22 U7 U15 V6 V14 V23 W3 W12 X11 X12 Y11 Y17 Y21 Z9
8	57	D20 D22 D23 E14 E23 G19 G20 H11 H13 I20 J12 K17 K21 K25 L2 M14 M21 N3 N4 N15 N23 O5 O10 O14 O16 O26 P2 P7 P27 Q11 Q12 Q16 Q25 R10 R23 S9 S10 S16 S25 T3 T6 T13 T19 U4 U10 V1 V11 V12 V13 W2 W8 W13 X14 Y12 Y20 AA10 AA14
7	64	A17 A19 B17 B20 G12 G16 G17 H10 J13 K12 K15 K18 L16 L17 L18 L21 M3 M4 M25 N8 N9 N11 N19 N24 O4 O13 O25 P3 P4 P8 P9 P10 P12 P13 P16 P28 Q3 Q5 Q7 Q10 R5 R22 R26 S15 T1 T9 U1 U12 U13 U19 V5 V9 V10 V21 W7 W9 W11 W14 W17 X13 Y13 Z13 AA11 AA13
6	56	B21 C17 D19 E18 E20 F17 F19 G11 G15 G18 I16 L22 L24 M16 M22 M24 N6 N25 O8 O11 O20 O21 P11 P22 Q4 Q6 Q9 Q17 Q18 Q22 R6 R7 R11 R17 R18 S4 S5 S6 S22 T2 T5 T7 T25 U3 U6 U11 V2 V15 V18 V19 W10 W15 X18 X21 Z11 AA12
5	35	C18 C20 D17 D18 E17 E19 F18 F21 G14 H16 I14 L14 M23 O12 O19 Q8 Q21 Q27 R13 R19 R21 S7 S8 S18 S19 T4 T10 U2 V8 V16 V17 W16 W19 X19 X20
4	23	C19 C21 D21 E21 F16 F20 G13 H15 K14 L15 L23 M5 M15 P17 Q19 Q20 Q26 R9 R12 R20 U5 W18 W20
3	10	F14 I15 J14 J15 N5 P18 P19 P21 R8 W21
2	4	S20 S21 T20 V20
1	1	U20

Table 4. Indicator values of the top ranked grid point based on an average ranking (I11) and an aggregation process (M13).

Grid Point	crop_ag	agcarb	aghq	agwq	agrec	SUM
I11	1050	−100	−150	−50	−75	675
M13	1500	−200	−300	−150	−100	750

First, the difference in the ranking methods should be emphasized. The top ranking of I11 is based on an average ranking where all five indicators are considered, whereas in the case of M13 the ranking is based on an aggregation, here a simple arithmetic sum, of the five indicators; thus, small values are compensated by large values.

A closer look at the figures leads to a clear explanation of the differences between I11 and M13, thus pointing at I11 as the optimal choice and partial ordering as a superior methodology. The problems associated with compensation effects when applying composite indicators has been discussed previously in several of papers dealing with partial ordering (cf., e.g., [2,10–14]).

It is clear (Table 4) that the outcome, crop_ag, of M13 is approx. 43% higher than for I11. Thus, a first look indicates that M13 is a more optimal choice that I11. However, focusing on the environmental impact, as visualized through the values of the five ES indicators, it immediate becomes obvious that the environmental impact in the I11 grid point is significantly lower that found for M13. Hence, in the latter case the high outcome overshadows, compensates the higher environmental impact. This leaves the decision maker with an obvious and highly relevant question: are we willing to sacrifice the environment in favor of a higher outcome from production?

Indicator Importance

In addition to the valuable information disclosing the grid point that on an average basis constitutes the optimal choice for the agricultural crop production, it appears to be of interest to verify the relative importance of the single indicators. This information is obviously of interest in order to clarify which of the ESs that play the most important role in the overall rating, thus, suggesting, e.g., which area where possible resources should be allocated in order to improve the environmental state of the area and possibly leave some additional space for a higher production rate. Such information is not available applying the composite indicator as ranking measure since the information is hided through the aggregation process.

The relative importance of the five indicators included in the study is estimated through a sensitivity analysis (cf. Section 2.4). The relative importance of the five indicators were found to be crop_ag (0.833) > aghq (0.093) > agwq (0.043) > agrec (0.021) > agcarb (0.009). It may not be surprising that the most important indicator is the actual production indicator crop_ag that account for close to 85%. For the ESs the result suggests that the most important ES is the habitat quality followed by the water quality, which, taking the crop production into account again may not be surprising. In the case of water, probably the water is used for irrigation that will obviously use water but not necessarily have significant impact on the quality, whereas clearing land for crop production may have significant impact on the habitat quality.

3.3. The Esgame-Ranching

The second part of the esgame is focused on production by ranching [20]. Obviously, the impact on the ecosystem services is different from those from agriculture by crop production. However, the overall picture is quite similar. Thus, we deal with 463 equivalence classes of which the by far biggest group is the one where all indicator values equal zero. As in the case described above, the resulting Hasse diagram features 12 level with 2, 11, 15, 36, 43, 44, 47, 49, 65, 70, 53 and 28 objects in the levels 1 to 12, respectively. The top 10 grid point based on an average ranking are L13 > E11 > P24 > O24 > P23 > M13 > X12 > R15 > F11 > Q23.

Hence, average ranking reveals the grid L13 as the most advantageous place for ranching, although based on the simple aggregation of the indicator values the Q23 grind point, which on an average basis has been assigned the rank 10, has the highest rank. In Table 5, the indicator values for the grid points L13 and Q23 are given.

Table 5. Indicator values of the top ranked grid point based on an average ranking (L13) and an aggregation process (Q23).

Grid Point	past_ps	pscarb	pshq	pswq	psrec
L13	800	−100	−125	−25	0
Q23	950	−100	−125	−50	−25

As in the agriculture example above, also here is seen that the maximum outcome is associated with grid point Q23. However, the increased outcome has been paid by an increased impact on the environment, i.e., an increased negative impact on the water quality and the hunting and foraging (cf. Table 1); thus, the same question as above arises: are we willing to pay for the increased outcome by an increased environmental degradation?

Turning to the indicator importance again, a picture close to that described above for crop productions is found, the relative importance being past_ps (0.810) > pshq (0.096) > pswq (0.057) > pscarb (0.023) > psrec (0.015). Again, the actual production indicator, past_ps, appears as the most important, not surprisingly followed by habit and water quality.

4. Conclusions and Outlook

The general applicability of partial order methodology for studying multi-indicator systems, as here the rating/ranking of land use has been elucidated based on a simple exemplary toy example adopted from a recent Chinese study and further by a significantly elaborate system, the data being taken from a recent game to study trade-off issues in agriculture and ranching. It has been demonstrated that a simple arithmetic aggregation of indicator values may well lead to the highest outcome, e.g., through crop production or ranching; this may not be consistent with focusing on the lowest negative impact on the ecosystem services. Thus, taking all indicators into account simultaneously, i.e., apart from the production outcome, also considering the impact on the involved ecosystem services such as water and habitat quality, carbon storage and Hunting and Foraging, a different picture develops. It is obvious that the higher production outcome apparently is overshadowed by an increased, and thus unwanted, deterioration of the ecosystem services. This obviously calls for an answer to the unavoidable question: do we want to accept a higher production outcome on the expense of the environment, here the ecosystem services? In other words, partial ordering leaves us with a clear picture of the relative influence of the single indicators, which in turn offers the regulators an efficient tool to focus on the specific targets that on an overall basis will improve the system at the most. Further, it is clear that such valuable information would not be provided when applying a composite indicator due to compensation effects. Hence, it is clear that aggregation may well lead to erroneous or, in the best case, questionable results [2].

The present study further demonstrates that partial order methodology constitutes a highly effective and advantageous tool to disclose the optimal solutions to handle complex multi-criteria issues, here illustrated by trade-off problems, e.g., the land use problem described here. Apart from the immediate overall average ranking the methodology further leads to a disclosure of the relative importance of the single indicators brought into play. As such, the partial ordering constitutes and advantageous multi-criteria decision support system applicable for analyses of a wide variety of multi-indicator systems without any pretreatment, e.g., aggregation of the included indicators, and thus, avoiding any misinterpretations due to compensation effects; eventually, in the present case, this leads to an optimal selection of land areas, taking both production outcome and ecosystem health into account.

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Essential Patents and Knowledge Position, a Network Analysis on the Basis of Patent Citations

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Abstract: Technology standards are considered important tools for increasing bargaining power and licensing revenues by combining the strategies of firms with the standard-setting organizations (SSOs) standardization processes. The essential patents declared by members of the SSOs play a critical role in such standardization processes. Some former researchers have found that, when using network analysis for measuring the knowledge positions in the "main-path" of standards-based markets, the essential patents did not match very well with the actual knowledge positions of the firms, in most cases. In this paper, we focus on the essential patents declared by the member firms in JTC1, an SSO that provides a standards development environment related to the development of the worldwide information and communication technology (ICT) standards for business and consumer applications, and that employs social network analysis techniques to investigate the knowledge positions of the patents, not only in the "main-path" discussed in the earlier literature, but also in the brokerage processes. We found that the brokerage-process approach helped us to better understand the roles of the essential patents that dominate transactions, relations, and the exchange of knowledge in the patent citation network than that of the main-path. Our findings suggest that claiming essentiality depends on the strategic behavior not only of the patents' owners, but also of the SSOs.

Keywords: standard-essential patents; technology standards; standard-setting organizations; social network analysis

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1. Introduction

As Bekkers and Updegrove (2012) [1], Baron and Pohlmann (2018) [2], and Baron and Spulber (2018) [3] have indicated, technology standards documents describe, define, and codify technologies. Technology standards define commonly accepted techniques, and reflect an agreement between different individuals, firms, or other entities, to use a particular method, which may be novel or not [2]. Technology standards may also govern access to technology because standard-setting organizations (SSOs) often require their members to license the proprietary technology that is necessary for the implementation of a standard, on specified terms [3].

On the other hand, technology standards can prescribe methods that are protected by patents. If a standard cannot be implemented without infringing on a patent, this patent is called a standard essential patent (SEP) [2]. Patented methods may also be useful, but not essential, for implementing a standard. A patented method is deemed commercially essential if it is considered indispensable for making any product that complies with the standard, or if existing alternative methods are technologically inferior or not accessible on commercially viable terms [1–5].

Some recent literature has focused on the values or knowledge positions of the SEPs, which people believe to be a critical factor in providing a competitive advantage to firms for extending their business [6]. The rationale is that the more essential patents that a firm owns and claims to the SSO, the stronger is its knowledge position [7,8]. However, on the other hand, Baron and Pohlmann (2015) [2] argue that many patented inventions are made during the process of standard development (e.g., to address a specific need or problem in a standardized technology), but are not included in the standard. This is because many different firms make contributions to the standards under development, and the contributions are subject to votes by SSO members.

In their recent study, Bekkers and Martinelli (2012) [9] indicate that claims of essentiality are the result of the strategic behavior of the patent's owner instead of actual technical relevance. By using a social network analysis on the patent citation network related to the 3G W-CDMA standard, they proposed an alternative indicator, i.e., a "main-path", to investigate the knowledge positions of the SEPs in the patent citation network, where they assumed that the main-path is an accurate description of the importance of the knowledge position in the patent citation network, and that most of the patents on this main-path should be claimed essential to the standard. However, they show that, among all claimed essential patents, only very few are on the main-path. They argue that the bulk of these claimed patents may be technologically unimportant, and that the link between the SEPs and the knowledge positions may be weaker than expected if people measure it by using the main-path analysis technique in the patent citation network.

Social network analysis has recently become a useful analytical tool, along with patent statistics [10,11]. Network-based techniques, such as the "main-path analysis", were pioneered by Hummond and Doreian (1989) [12]. In the recent past, a number of papers employed this approach for mapping technological trajectories [13–15]. Specific algorithms can be used to identify the "main flow of knowledge" within the patent citation network. This main flow of knowledge is a set of connected patents and citations linking the largest number of patents of the network, thereby accumulating the greatest amount of knowledge flowing through the citations. This path represents, therefore, a local and cumulative chain of innovations consistent with the definition of a technological trajectory. Given the success of this approach in understanding the main flow and the development of patented knowledge, it might be promising for providing insight into the knowledge positions of the firms that own those patents. However, as indicated in Bekkers and Martinelli (2012) [9], the granularity of this method might restrict its usability in this context: even if the full network comprises thousands, or even ten thousand patents, the identified main-path of knowledge is often comprised of a few dozen patents, or even less. This "over selective" problem may result in serious limitations and lead to a misunderstanding of the knowledge positions of the SEPs. On the other hand, Gould and Fernandez (1989) [16] propose a knowledge broker typology framework. The advantage of the broker position in a network is that the participants who are positioned as information brokers between groups with different information backgrounds benefit from information flows, have a positive influence on their quantitative and qualitative output, and can even induce competition or conflict between neighbors who are not linked directly.

In this paper, we attempt to investigate the relationship between the patent claimed by its owner to be essential and the knowledge position of the patents in the patent citation network. We focus on the knowledge positions not only in the "main-path" discussed in the earlier literature, but also in the brokerage processes.

We pay attention to essential patents declared by member firms in JTC1, an SSO that provides a standards development environment related to the development of worldwide information and communication technology (ICT) standards for business and consumer applications.

Our paper offers three main contributions. Firstly, we verified the result of the former research [9] from an entirely different standards-based high-tech field, i.e., the JTC1 main-path. Secondly, in addition to the results of the analysis of the "main-path", we provide our results for the patent citation networks with other characteristics, e.g., betweenness centrality, and brokerage roles, etc., and obtain a different finding, suggesting a strong correlation between the SEPs and their brokerage roles. Finally, we also implement regression analyses for the determinants of the strategies of the SSO members related to the declaration of the

SEPs by employing the timing for cooperation and entry into an industry SSO, and the patent portfolios of the SSO members.

The paper is organized as follows: in Section 2, we describe our dataset; in Section 3, we discuss the social network analysis on the patent citation network; in Section 4, we provide the regression results for the determinants of the declaration of the SEPs; and Section 5 concludes.

2. Materials and Methods

In order to test whether the above methodologies result in good indicators of knowledge positions, we needed appropriate data for our selected case. The essential patent analyses, obviously, requires a dataset of the essential patents, whereas network-based analyses require a dataset that contains information about the patent citation relations between these patents. Below, we will briefly describe the datasets and methods.

2.1. Essential Patents in the JTC1

As data are most constrained for standard-essential patents, we collected our data for standard essential patents from the Disclosed Standard Essential Patents (dSEP) Database, developed by Bekkers et al., (2012) [17]. The database is based on the archives of thirteen major SSOs and provides a full overview of all of the disclosed IPRs at setting organizations worldwide. The dSEP is cleaned and harmonized, and all of the disclosed patents, or patent applications, of the United States Patent and Trademark Office (USPTO), or the European Patent Office (EPO), are matched against the patent identities in the Worldwide Patent Statistical Database (PATSTAT).

As discussed in Section 1, we focus on JTC1, an SSO that provides a standards development environment related to the development of worldwide ICT standards for business and consumer applications. Since its inception in 1987, JTC1 has brought about a number of very successful and relevant ICT standards in the fields of multimedia (e.g., MPEG), IC cards ("smart cards"), ICT security, database query, programming languages, as well as character sets. Our sample includes 1,149 SEPs, declared by 63 JTC1 member firms, during the period from 1990–2010. Since the JTC1 includes more than 400 technology standards, the member firms may declare the same patent to different standards. Thus, we identified 387 patents, of which 276 patents were published in the USPTO, and 111 were published in the EPO. Then, we used "docdb_family_id", a unique code defined by the PATSTAT for identifying patent families, to clean our sample, and we finally obtained 241 standard essential patents published in the USPTO.

2.2. Patent Citations

In the dSEP, every essential patent has a unique and universal application identification, named the "appln_id", as defined by the PATSTAT, which allowed us to be able to merge all the SEPs listed in the dSEP with the information for those patents in the PATSTAT. We then utilized the information of the patent citations for the USPTO patents in the latter database.

Patent citations presumably convey information or knowledge flows between innovations or patent holders. As shown in Figure 1, we concentrated our sample on the patent citation relationships between the JTC1 member firms' patents. We also included patents held by firms that are not JTC1 members if they cited the SEPs or were cited by the SEPs. Thus, after deleting the biased citations in which the year cited is later than the year citing, we obtained more than 15,000 pairs of patent citations that were cited during the period of 1990–2010 in our sample.

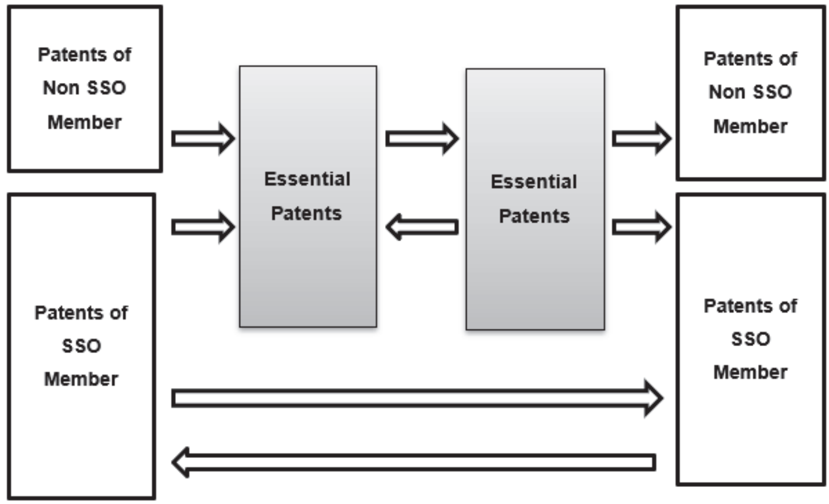

Figure 1. Patent citation relationships for the sample.

2.3. Main-Path Analysis in Social Network Analysis

The developments in the field of social network analysis have created several software tools that can facilitate the visualization, analysis, and interpretation of cooperation and citation networks, such as R, Pajek, Gephi, etc,. At the same time, these software tools can also explain the relationships between technology fields, patent applications, inventors, applicants, etc. Furthermore, the tools facilitate and support the combination of the qualitative and quantitative analyses of social networks, allowing for the construction of an index to explore the characteristics of the network for the applications on knowledge learning, knowledge flows, transfers, etc. [16,18–22].

In general, an item receiving more citations is deemed to be of more importance. In most citation networks, however, all patents are linked in one bicomponent. This cohesion concept does not take time into account. It does not reflect the incremental development of knowledge nor does it identify the patents that were vital to this development. Therefore, a special technique for citation analysis was developed that explicitly focuses on the flow of time. It is called "main-path" analysis [12].

Let us think of a citation network as a system of channels that transports scientific knowledge or information. A patent that integrates information from several previous items and adds substantial new knowledge receives many citations, and it will render the citations to previous patents more or less redundant. As a consequence, it is an important junction of channels and a great deal of knowledge flows through it. If knowledge flows through citations, a citation that is needed in the paths between many patents is more crucial than a patent that is hardly needed for linking patents. The most important citations constitute one or more main-paths, which are likely to be the backbones of a technology tradition.

Main-path analysis calculates the extent to which a particular citation or patent is needed for linking patents, which is called the traversal count, or traversal weight, of a citation or a patent. First, the procedure counts all paths from each source (a patent that is not citing within the dataset) to each sink (a patent that is not cited within the dataset), and it counts the number of paths that use a citation by the total number of paths between the sources and sink vertices in the network. This proportion is the traversal weight of a citation. In this paper, we employ an algorithm called the search path link count (SPLC), that weights each edge proportionally to how often a given link is present in all the paths that can link between any start point (i.e., patents that do not cite any other patent) to any endpoint or sink (i.e., patents that do not receive any citation). Thus, the paths with the highest SPLC values are more likely to be on the main-path.

Bekkers and Martinelli (2012) [9] assume that the main-path is an accurate description of the most important contributions to the field, and one might expect that most of the patents on this main-path are indeed claimed to be essential to the standard.

2.4. Brokerage Roles in Social Network Analysis

The approach to brokerages and affiliations may help us to better understand the roles of patents that dominate a transactional, or exchange of knowledge, network. The roles of the actors in the network can be quite divergent and are categorized as "itinerant", "representative", "gatekeeper", and "liaison". The approach of the knowledge brokerage analysis has been identified as a promising strategy for investigating knowledge positions [18–21,23,24].

Group affiliation is often important in the brokerage process [23,24]. In real-world patent citation relationships, patents tend to be cited within the same field, and the patent that mediates between different fields plays the brokerage role. We may imagine that a patent, B, in the manufacturing field is cited to another patent in the IT field; for the knowledge transfer path, patent B is important because whoever owns B has a strong negotiating position and the chance to strike a good deal, and the removal of B disconnects the knowledge transfer path. In our paper, the patents in the same field, or that are often cited mutually, are comprehended as a group, and we wanted to find out if patents act as brokerage roles in our sample.

Figures 2–6 depict the categories, where the triad in which actor B mediates the transactions between actor A and actor C can display five different patterns of field affiliations:

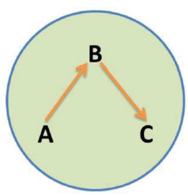

Figure 2. Coordinator.

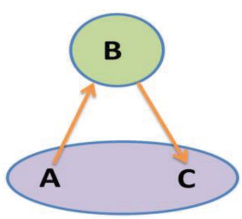

Figure 3. Itinerant.

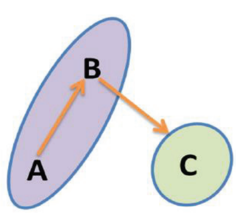

Figure 4. Representative.

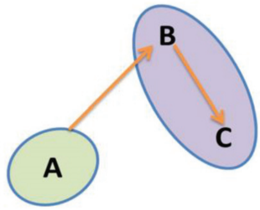

Figure 5. Gatekeeper.

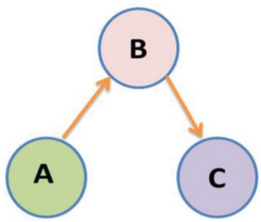

Figure 6. Liaison.

- In the "coordinator" triad, all actors, including broker B, and the source of knowledge, are in the same group.
- In the "itinerant" framework, broker B mediates between the actors, A and C, that are in the same group, but broker B is not part of this group.
- The "representative" role is given if a cluster delegates the role of brokering external knowledge to someone in the other group.
- The "gatekeeper" screens external knowledge and distributes it within its own group.
- "Liaison" refers to when the knowledge is brokered across different groups, none of which broker B is a member of.

2.5. Other Covariants

We acquired data related to the determinants of the strategies of the SSO member firms on the SEPs from the Searle Center Database [3]. The data comprises the number of employees, the number of patent applications, and the ratio of R&D expenditure to total sales for the JTC1 member firms in the sample period. With regard to the timing for cooperation and entry into the JTC1, we employed the year of the first pool launch for the JTC1 that was also released in the Searle Center Database. All statistical descriptions are shown in Table 1.

Table 1. Statistical descriptions (1).

Variable	Obs	Mean	Std. Dev.	Min	Max
No. of Employees	2419	80,416	70,646	1	264,880
Sales (MM US$)	2270	25,300	17,987	1	71,186
No. of Patent Applications	2229	2692	3459	2	11,424
R&D Expenditure (MM US$)	2254	1952	1369	1	3872
Year of First Pool Launch	2392	1995	5	1990	2005

3. Social Network Analysis

This section highlights some characteristics of patents in the JTC1 by employing methodologies currently developed in practice. These types of network analyses allow for the identification of the important players in the JTC1, and their connectedness, which can be used in the analyses of competitors or partners in this SSO.

3.1. Investigating the Presence of Essential Patents on the Main-Path

To implement the network analysis, we used Pajek 5.0.9, a software tool for analyzing social networks [24], to measure the SPLC values for the main-path in the patent citation network. Figure 7 illustrates a selected citation network in which the values (or weight) of the SPLC were larger than 0.004. The network consists of 180 patents, and out of those, the 41 patents with the sky-blue marks are the SEPs. Figure 7 also shows, in a solid line, the main-path with the highest SPLC values. The main-path comprises a total of eighteen patents, of which five patents are essential patents, and thirteen patents are other patents that are not claimed by the SSO member firms.

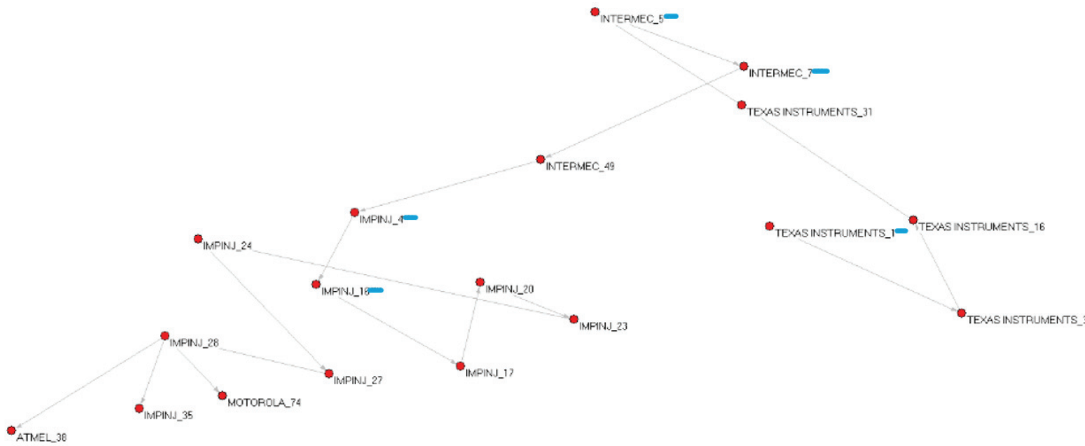

Figure 7. Main-path in selected citation network. Note: patents with sky-blue marks denote essential patents claimed by their owners.

Furthermore, Table 2 and Figure 8 reveal the distributions of the SPLC values for the SEPs, as well as the patents that are not claimed in the selected network. Although the average values of the SPLC for the SEPs are larger than those for non-claimed patents, compared with the latter, the former does not overwhelmingly contribute to the main-path. Thus, our finding in the JTC1 is consistent with that in Bekkers and Martinelli (2012) [9].

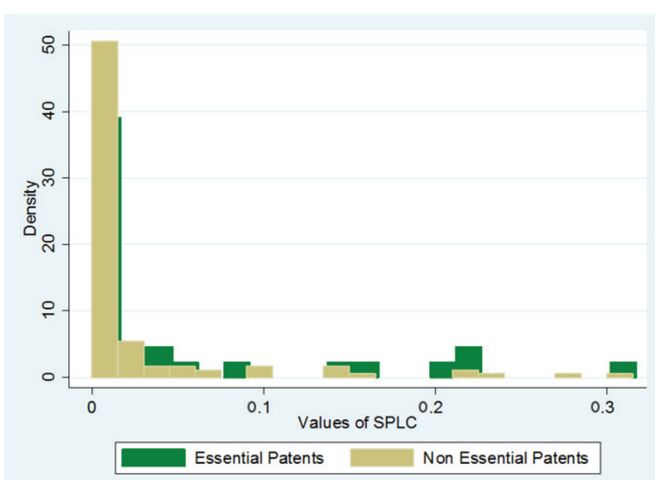

Figure 8. Histogram of the values of SPLC in selected network.

Table 2. Quantile of the values of SPLC in selected network.

	Values of SPLC									
	Mean	**1%**	**5%**	**10%**	**25%**	**50%**	**75%**	**90%**	**95%**	**99%**
Non Essential Patents	0.00135	0.00000	0.00000	0.00000	0.00001	0.00002	0.00009	0.00059	0.00179	0.01812
Essential Patents	0.00695	0.00000	0.00000	0.00000	0.00002	0.00006	0.00046	0.00334	0.01258	0.21333

3.2. Visualization Analysis on Brokerage Roles

While the main-path approach is widely used, and results in a valid representation of the main-path of technological development, such an approach is likely to face serious limitations. The question is whether such an "over selective" path lacks the necessary degree of granularity. Some companies might have contributed important knowledge, but their patents are not part of the main-path themselves. Recognizing these restrictions, this paper proposes an alternative approach that makes it more apt to evaluate knowledge positions, that is, the brokerage-role approach.

Social ties are one measure of social capital that can be used by actors for positive advantages. If we pay attention to the ties between an actor's contacts, an actor that is connected to actors who are themselves not directly connected has opportunities to mediate between them, and to profit from this mediation [23].

Research into brokerage roles is concerned with describing the types of brokerage roles that dominate a transactional or exchange network. In addition, individual positions within the network may be characterized by the dominant type of brokerage role, and hypotheses may be tested about the personal characteristics of individuals with certain types of brokerage roles.

Figures 9–12 demonstrate the values of "itinerant", "representative", "gatekeeper" and "liaison" for the selected network, which were measured by the Pajek. The size of the nodes shows the extent to which the patents play a particular brokerage role in the patent citation network. Because the values of "coordinator" are highly correlated with those of "itinerant", we discarded them from our analysis. The number of brokers in full network, and statistical descriptions for those brokers are summarized in Tables 3 and 4.

The size of the nodes counts the frequency of broker roles in our network. For example, patent no. 5, from INTERMEC Co., plays "itinerant" and "liaison" many times, but has no role as "representative" or "gatekeeper", so it has a large size in Figures 9 and 12, but a tiny size in Figures 10 and 11.

Figure 9 shows that, among the ten patents with the largest values of "itinerant", only no. 5 and 49 of the patents from INTERMEC Co. are located on the main-path, which is described by a solid line, while the other eight patents (no. 6, 41, and 49 from INTETMEC; no. 10 from SYMBOL TECH; no. 1 from MATRIC; no. 1 from ZEBRA TECH; no. 4 from ALIEN TECH; no. 14 from TEXAS INS; and no. 1 from BTG INT) are far from the main-path. Furthermore, out of the ten patents, only two are nonessential patents. Thus, the brokerage approach provides us with more information for understanding the roles of the SEPs, compared with the main-path approach.

At the same time, as can be seen from Table 3, among the 241 SEPs, approximately 76 and 81% of the SEPs play the roles of "itinerant" and "liaison", respectively, while those of the patents not claimed are less than 2%. Our findings suggest that there is a strong relationship between the broker roles, such as "itinerant" and "liaison", and the SEPs, which means that the patents that serve as "itinerant" and "liaison" may be more likely to be claimed as SEPs. On the other hand, however, only 2.9% of the essential patents are "representative", and 1.66% of the essential patents are "gatekeepers", which are not significantly different than the 1.98 and 1.12% for the patents not claimed.

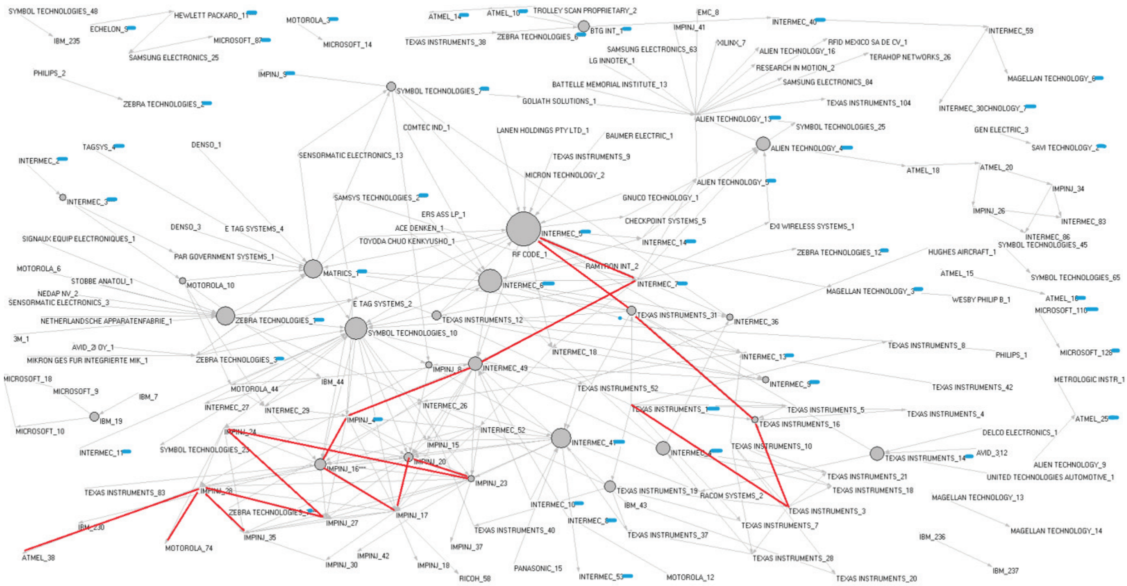

Figure 9. Values of "itinerant" in selected network.

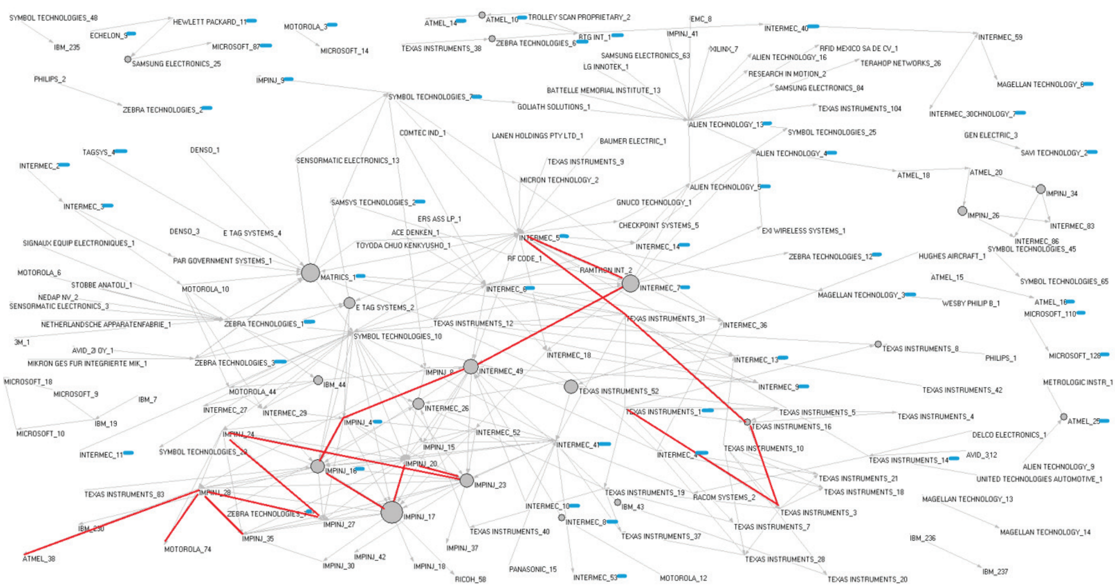

Figure 10. Values of "representative" in selected network.

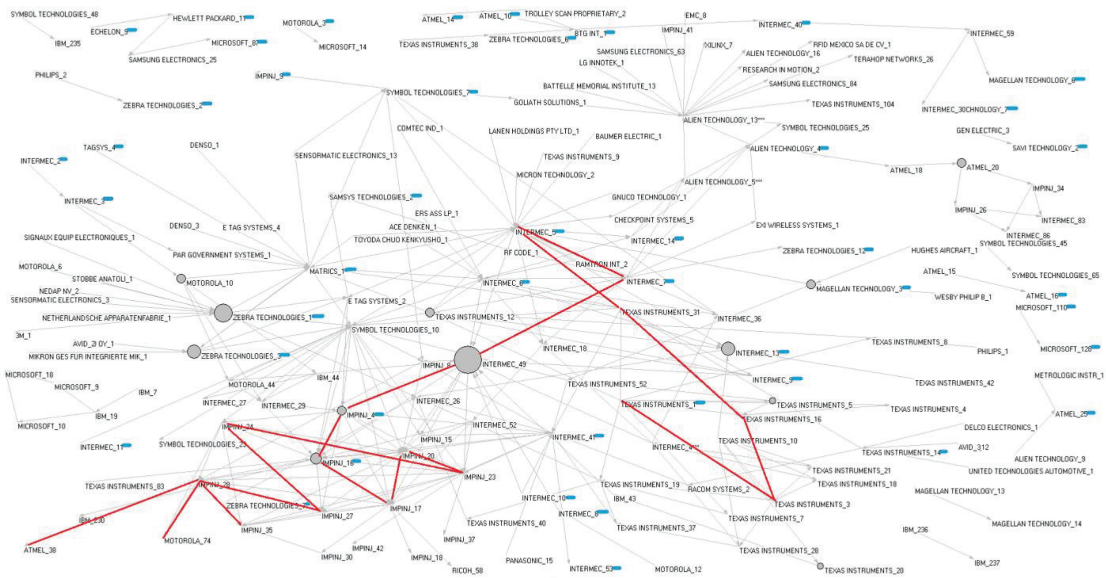

Figure 11. Values of "gatekeeper" in selected network.

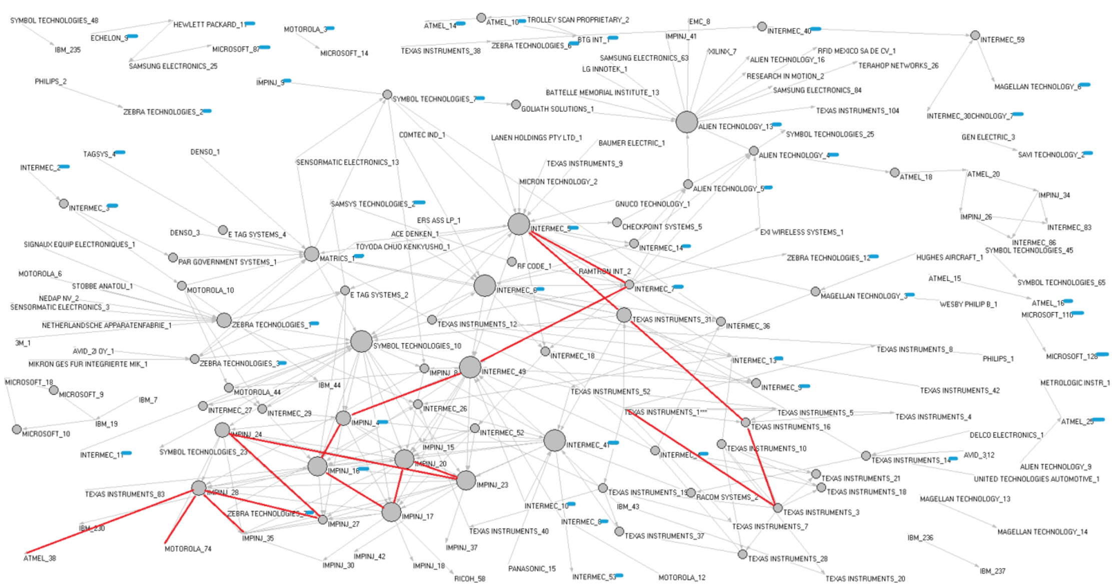

Figure 12. Values of "liaison" in selected network. Note: patents with sky-blue marks denote essential patents claimed by their owners in Figures 9–12.

Our social network analysis provides evidence that we are confronted with a selection effect: the values of essential patents are not only more strongly cumulative, but also more valuable than the nonessential patents from their technological field. This could result from the fact that the SSOs often choose between different technological options and select the best technologies for inclusion into the standard. We also find that the SPLC values of the essential patents are not absolutely larger than those of the nonessential patents, which implies that the patents claimed to be essential are not necessarily on the main-path.

Table 3. Number of brokers in full network.

	Number of Brokers		
Roles of Brokers	**Nonessential Patents**	**Essential Patents**	**Total**
Itinerant	49 (1.90%)	183 (75.93%)	232 (100.00%)
Liaison	338 (1.12%)	194 (80.50%)	532 (100.00%)
Representative	29 (1.12%)	7(2.90%)	36 (100.00%)
Gatekeeper	51 (1.98%)	4(1.66%)	55 (100.00%)
Total	2581	241	

Table 4. Statistical descriptions (2).

Variable	Obs	Mean	Std. Dev.	Min	Max
Dummy for Essential Patents	2822	0.085	0.280	0	1.000
Values of SPLC	2822	0.002	0.016	0	0.311
Betweenness Centrality	2822	0.002	0.011	0	0.218
Itinerant	2822	4.914	44.638	0	1220.000
Liaison	2822	22.427	176.095	0	4529.000
Representative	2822	0.053	0.720	0	22.000
Gatekeeper	2822	0.047	0.471	0	14.000

4. Empirical Analysis on the Relation between Main-Path, Brokerage Roles, and SEPs

The aim of this section is to empirically explore the relations between the main-path, brokerage roles, and the SEPs, and investigate the determinants of the SEPs.

We build a dependent variable related to the SEPs, where it equals the unit if the patent is claimed to be essential, and it is zero otherwise.

We also consider the regressions with the index for "betweenness centrality", which calculate the extent to which an actor (or a patent) is located on the shorted path between any two nodes in the patent citation network. Betweenness centrality captures both the centrality and the spanning of structural holes in the network [25]. For an actor (or patent), *i*, its value of betweenness centrality can be measured by:

$$Betweenness\ Centrality_i = \sum\nolimits_{j \neq k \neq i} \frac{g_{jk}(i)}{g_{jk}}$$

where $g_{jk}(i)$ denotes the number of shortest paths linking actors, *j* and *k,* that contain the focal actor, *I* and g_{jk} is the total number of shortest paths from actor *j* to actor *k*.

4.1. Baseline Regressions

Table 5 presents the results of the regression analyses for the impacts of the SPLC value and brokerage roles on the patents claimed as SEPs. First of all, the coefficients for the "itinerant" are strongly positive and significant in both of our two regression models, indicating that the patents with the itinerant position are more likely to be claimed essential.

The liaison is not significant against the null, which may be due to the multicollinearity problem (see the correlation coefficients in Table 5). We tested the variance inflated factor (VIF) for all the independent variables in Table 6. The VIF is up to 3.83 for the "liaison", relative to 3.44 for the betweenness centrality, 1.55 for the "itinerant", and 1.0 for the three other variables. Although there is a debate about the critical values of the VIF, according to Hair et al., (2010) [26], if the VIF value is around, or exceeding, 4.0, then a problem with multicollinearity should be considered. Thus, we excluded the "liaison" in the second regression model, and the "itinerant" stayed the same.

At the same time, the coefficients for the "representative" were also positive and significant. However, the significance level seemed to be weak. In contrast to those for the "itinerant" and "representative", however, we can find that the coefficients for the SPLC value are not significant in either of our models, which again verified our conclusion that patents on the main-path are not necessarily essential patents.

Table 5. Correlation coefficients of variables.

	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
1. Dummy for Essential Patents	1.000											
2. Values of SPLC	0.114	1.000										
3. Betweenness Centrality	0.297	0.054	1.000									
4. Itinerant	0.376	0.036	0.461	1.000								
5. Liaison	0.325	0.022	0.728	0.534	1.000							
6. Representative	0.019	−0.006	0.020	−0.006	0.024	1.000						
7. Gatekeeper	−0.018	0.023	0.050	−0.008	0.004	−0.008	1.000					
8. No. of Employees	−0.051	−0.019	−0.071	−0.051	−0.053	−0.035	−0.037	1.000				
9. Sales	−0.025	−0.040	−0.074	−0.031	−0.023	−0.020	−0.058	0.917	1.000			
10. No. of Patent Applications	−0.113	−0.025	−0.072	−0.056	−0.052	−0.025	−0.062	0.252	0.237	1.000		
11. R&D Expenditure	−0.014	−0.051	−0.001	0.008	0.067	0.040	−0.023	0.304	0.550	−0.011	1.000	
12. Year of First Pool Launch	0.093	0.085	0.096	0.033	0.017	0.028	0.097	−0.496	−0.592	−0.406	−0.379	1.000

Furthermore, the coefficient for the betweenness centrality is not significant, indicating that high betweenness centrality values are not contributing to a firm's patents being claimed essential.

Table 6. Baseline estimations with logit regression model.

Covariables	**I**	**II**
Dependent Var:		
Dummy for SEPs		
Values of SPLC	5.286	5.413
	(1.11)	(1.12)
Itinerant	0.656 ***	0.705 ***
	(4.65)	(4.56)
Liaison	0.005	
	(0.80)	
Representative	0.152 *	0.159 **
	(1.74)	(2.09)
Gatekeeper	0.152	0.147
	(1.09)	(1.03)
Betweenness Centrality		16.035
		(1.48)
Log Likelihood	−232.77	−233.30
No. of Obs.	1819	1819

Note: (1) All regressions include fixed effects for the SSO member firms. (2) The values in the parenthesis are t statistics. (3) "***", "**", and "*" denote significance levels at 1, 5, 10% respectively.

4.2. Estimates for Determinants of Strategies Related to the SEPs

Table 7 allows us to underline a couple of the results. First, we can obtain the same conclusion as Table 6: that a strong link exists between the declaration to be essential and the patents serving as "itinerant" and "representative". Moreover, the coefficients for the SPLC and the betweenness centrality allow for the refinement of the previous results from the last table. Furthermore, the firms in the "gatekeeper" position do not seem to help their patents to be claimed essential.

With regard to the determinants of the strategies of the SSO member firms, the estimates of the number of patent applications and the R&D intensity are revealed to be positive and significant in some cases, suggesting that the SSO member firms with larger patent portfolios, and that engage in more R&D activities, are more likely to claim their patents to be essential. However, the impacts of the number of employees are mixed.

Table 7. Logit estimates for determinants of strategies related to SEPs.

	I	II	III	IV	V	VI	VII	VIII
Dependent Var: *Dummy for SEPs*								
Values of SPLC	7.455	5.582	7.237	7.237	7.183	5.534	7.119	7.119
	(1.35)	(1.12)	(1.31)	(1.31)	(1.29)	(1.12)	(1.29)	(1.29)
Itinerant	0.653 ***	0.671 ***	0.658 ***	0.658 ***	0.559 ***	0.640 ***	0.562 ***	0.562 ***
	(4.47)	(5.68)	(4.54)	(4.54)	(5.34)	(4.89)	(5.33)	(5.33)
Liaison	−0.006	−0.002	−0.006	−0.006				
	(−0.75)	(−0.29)	(−0.78)	(−0.78)				
Representative	0.149 **	0.159 **	0.149 **	0.149 **	0.146 **	0.158 **	0.146 **	0.146 **
	(2.28)	(2.28)	(2.27)	(2.27)	(2.20)	(2.25)	(2.20)	(2.20)
Gatekeeper	−0.473	−0.274 **	−0.478	−0.478	−0.482	−0.273 **	−0.485	−0.485
	(−0.74)	(−2.32)	(−0.75)	(−0.75)	(−0.77)	(−2.35)	(−0.77)	(−0.77)
Betweenness Centrality					5.508	10.438	4.018	4.024
					(0.31)	(0.90)	(0.21)	(0.21)
Log of Employees	1.215 ***	−2.161 ***		1.460 ***	1.180 ***	−2.158 ***		1.252 ***
	(4.79)	(−3.95)		(3.29)	(3.91)	(−4.14)		(3.26)
Log of Patent Applications	0.175		1.514 ***	0.304	0.183		1.279 ***	0.241
	(0.70)		(3.01)	(1.08)	(0.73)		(2.98)	(0.90)
Ratio of R&D to Sales	31.603 **				29.487 *			
	(2.08)				(1.78)			
Year of First Pool Launch	−0.006	0.372 ***	0.461 ***	0.197 *	−0.006	0.350 ***	0.373 ***	0.147
	(−0.06)	(4.33)	(2.93)	(1.87)	(−0.06)	(3.77)	(2.74)	(1.48)
Log Likelihood	−168.46	−186.76	−168.38	−168.38	−168.96	−186.70	−168.91	−168.91
No. of Obs.	1287	1409	1287	1287	1287	1409	1287	1287

Note: (1) All regressions include fixed effects for the SSO member firms. (2) The values in the parenthesis are t statistics. (3) "***", "**", and "*" denote significance levels at 1, 5, 10%, respectively.

What is noticeable is that the coefficients for the "year of first pool launch" are strongly positive and significant for our five models. We can infer from this result that the new patents launched in the pool are more likely to be claimed essential. This may be due to the fact that SSO member firms make contributions to standards under development. The later the firm first launches the SEPs to the pool, the more it claims the patents to SEPs.

5. Conclusions

In this paper, we implemented the empirical analysis of the knowledge positions of firms in high-tech standards-based markets by using the patent data at the firm level. We believe that being able to assess the knowledge positions is important because they are assumed to increase the chances for sustainable market participation, bargaining power, and licensing revenues. Our study focused on the JTC1, an SSO that provides a standards development environment related to the development of worldwide ICT standards for business and consumer applications. We attempted to utilize the social network technique to find out the characteristics, i.e., the "main-path", the "betweenness centrality", and the brokerage roles in the patent citation network of the JTC1, and carried out a regression analysis of the effects of these characteristics on the declaration of the SEPs. Our main conclusions are:

- Patent citations are used as a tool for mapping technological trajectories, and the main-path analysis has been widely used in previous research. The main-path analysis does identify the most important technological advances and breakthroughs in the development of this technology; however, it is too selective to fully assess the knowledge positions of firms.
- To fill this research gap, we investigated another social network analysis method: the brokerage-roles approach, which results in a better measurement of the knowledge positions, and more suitably matches the outcomes of the historical/technical narrative and analysis of knowledge flows. We also implemented an empirical analysis to support our findings based on the social network analysis, and empirical results

revealed that, the relationships between the brokerage roles and the SEPs are strongly significant in our sample, while it is not the case for the main-path values.

- While investigating the deep-seated reasons for the former two conclusions, we found that claims of essentiality are the result of the strategic behavior of the patent's owner. As important patents often occupy brokerage positions, we can infer from our results that firms usually tend to pursue their knowledge positions in the standard activities, or a competitive advantage in their international business, by claiming their really important patents to be essential in the standardization.

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Data Availability Statement: We collected our data for standard essential patents from the Disclosed Standard Essential Patents (dSEP) Database developed by Bekkers et al., (2012). The data are available in a publicly accessible repository: http://ssopatents.org/ (accessed on 3 September 2021). We acquired patent citation data from the patent dataset, PATSTAT ver. October 2016. PATSTAT, also known as the EPO Worldwide Patent Statistical Database, is a snapshot of the EPO master documentation database (DOCDB), with worldwide coverage, covering more than 20 tables, with bibliographic data of about 70 million for the patents issued by most of the patent institutes in the world. See https://www.epo.org/index.html (accessed on 3 September 2021). We acquired data related to the determinants of the strategies of the SSO member firms on the SEPs from the Searle Center Database. The data are available in a publicly accessible repository: http://www.law.northwestern.edu/research-faculty/searlecenter/innovationeconomics/data/technologystandards/ (accessed on 3 September 2021).

Conflicts of Interest: The authors declare no conflict of interest.

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Standards for the Weighting of Criteria and the Measurement of Interaction

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Abstract: This article discusses the need for standards for the assignment of importance to criteria and the measurement of interaction between them in multiple criteria analyses of complex systems. A strategy for criteria evaluation is considered that is suitable to account for the interaction among a wide variety of imprecisely assessed criteria applied simultaneously. It is based on the results of collecting sample information on preferences according to the specified criteria instead of merely an abstract comparison of the criteria. The comparison of alternatives is based on objectives that determine the formation of preferences. It is facilitated by a rating in terms of preference probabilities. Probabilistic standards grant homogeneity of measurements by different criteria, which is useful for the combination of the criteria. These standards apply to a sampling evaluation conducted via pairwise trichotomic comparison of the alternatives according to each criterion, followed by the combination of these multiple evaluations into a single global score by means of the Choquet Integral with respect to a capacity determined by applying preference concentration to the sets of probabilistic assessments. Examples of practical application are discussed.

Keywords: multiple criteria decision analysis; rating; rankings; interaction; Choquet capacity

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1. Introduction

The main motivation for this study comes from the need for standards for the assignment of importance to criteria and for the modeling of the interactions between them in a multiple criteria decision analysis (MCDA) dealing with a large variety of criteria subject to random disturbances and interacting with each other. The abundance of distinct methods in the field [1,2] makes the search for such standards more relevant. Standards streamline decisions, for instance, in situations such as making an emergency health decision [3], facing a sudden enemy military attack [4], offering advice regarding stock trading under volatile market conditions [5], or choosing a supplier for a failing critical component [6].

Another aspect of situations that makes the establishment of standards important is the complexity and subjectivity of the application of the related criteria [7,8]. As a consequence, it is important not only to simplify the measurements but also to make them comparable and to ensure that the relations between the measurements according to different criteria, the forms of criteria importance assessment, and the criteria combination rules can be easily explained. In these situations, combining a large variety of criteria, avoiding arbitrarily assigning unequal importance to them, and accounting for the complexity of their relations necessitates a set of simple and well-defined standards governing the key analysis procedures.

One situation involving complex and subjective decisions is that of the prediction of electoral preferences. Electoral preference prediction models can be classified into two categories: fundamental models and polling models. Fundamental models attempt to derive votes from economic and social explanatory variables. Polling models address only the final voting preferences. They pose the single question: "if the election were today, who would you vote for?"

Due to a low predictive power observed in the models of the first category, the currently prevailing models tend to combine variables from poll models with other variables, which mostly serve to evaluate the personal qualities of the candidates or the approval of parties' incumbents [9–11]. Formulating the choice in terms of individual preferences regarding individual qualities strengthens individualistic motives.

Behind such an assessment model for individuals is the rational choice assumption that the members of the sample weigh their reasons mentally. In contrast, by making explicit the multiple objectives that interact in the formation of personal preference, complex MCDA models emphasize these objectives themselves. In an assessment of the preferences of the population, this has the effect of strengthening the pursuit of the common good. To project a long-term goal, a nation must have it as a collective target.

Collective objectives that lose importance in the modeling of preferences also lose importance in the culture in which those preferences are formed. In contrast, the modeling of preferences based on matters of collective interest will favor the prevalence of a culture of collaboration around collective goals. If elicited in preference assessments, the positioning with respect to civil rights, the size of the government, environmental protection, development goals, and other objectives of high importance will, in turn, be more present in the political scenery.

In recent years, modern economic growth theory has shifted from the classical theory emphasizing capital and labor productivity to a theory emphasizing the roots of productivity in the form of ideas and institutions [12]. Countries that are open to ideas invest in education and create efficient institutions. The predictions based on economic and social objectives supply the motivation for these efforts.

From a parsimony perspective, a small number of variables with high predictive power for certain aspects of the decision can make a prediction model more efficient. To become competitive, models encompassing a large set of interacting variables must be supported by efficient fitting strategies.

The standard procedures in MCDA provide for the safe consideration of a large number of objectives that drive the choice of a model. These standards should be simple but comprehensive to allow for models that capture the complexity of the reality to be addressed.

The development of such standards is, then, an important research issue, and the lack of a reliable set of standards constitutes a serious gap in the MCDA research area. The present study fills this gap.

Here, standards for combining preferences established by multiple criteria whose importance is derived from their ability to identify the most preferred alternatives are discussed. Included are standards for the comparison of alternatives according to each criterion [13,14], standards for the combination of evaluations based on separate criteria into a global score [15,16], and standards for the measurement of the importance of interacting criteria [17–19]. The development of an analysis applying these standards will always serve as a basis for the comparison of the results of the application, in every case, of any MCDA method recommended by the peculiarities of the case.

The article is structured as follows. After this introduction, Section 2 sets the foundations for establishing standards for data collection, criteria comparison, and evaluations combination. Desirable properties of the decision rules are then established. Section 3 deals with the application of the principles and procedures advanced in the preceding section. Section 4 discusses the results obtained in Section 3 based on the analysis of practical situations. A set of conclusions on the viability and the usefulness of the standards established is presented in Section 5.

2. Materials and Methods

To be able to account for a wide variety of criteria, the assessment of preferences must be simple. By reducing the opportunities for the occurrence of errors in the measurement, simplicity engenders reliability.

Another important quality is comparability. To combine preferences among the alternatives being evaluated according to diverse criteria to obtain global scores, it is necessary to determine measurement standards that make the preferences assessed comparable in accordance with the different criteria.

An even more fundamental feature is representativeness. Alternatives must be evaluated based on their degree of commitment to an objective that is considered relevant to sustaining a criterion. How can such degrees of commitment be measured in a simple and comparable form?

The sampling of pairwise trichotomic comparisons exhibits all the desired properties. This assessment standard consists of assessing a sample of randomly selected representatives, either of the population or of experts, to determine, for every pair of alternatives, whether each of them is more capable than the other of reaching the desired objective. In the case of a tie, the preference measure is equal for both.

The small number of possible values, namely three, enhances robustness [20,21]. For instance, if, in a more detailed preliminary assessment, a distorted "very high" preference classification is given to one alternative, this alternative shares, in the comparison with an alternative with a "small" initial evaluation, the same preference assessment with any other alternative with a "high" classification.

If different scales of measurement of a single attribute have different meanings for different objectives, this same attribute may be used in different criteria with different roughness [22,23]. For instance, a complementary criterion can be built by imposing a transitivity requirement on experts' ratings to tie more pairs of alternatives.

In the same sense, if considering more precise distances between alternatives is found to be useful, additional criteria can be created to represent narrower levels of variance. For instance, in a first criterion, two alternatives may be considered equivalent if the difference between their values in a certain attribute is smaller than 10, whereas, in a second criterion, they may be considered equivalent only if the difference is smaller than 1.

Counting the number of pairs exhibiting a preference for each alternative serves as the basis for calculating preference probabilities. Shifting from attribute measures to probabilities of preference has the benefit of unifying all evaluations to the same scale of measurement. This property of the commensurability is an essential condition to enable the combination of the criteria by means of the Choquet Integral [24].

From assessments of preference based on diverse criteria, we need to move to a measure of preference that considers all the criteria collectively. Counting favorable cases in pairwise trichotomic comparisons may still be useful to measure joint preference. However, this count does not consider the interactions between criteria. For such a calculation, the Choquet Integral of the preference probabilities according to each criterion is the simplest form. It will be calculated with respect to a capacity designed to adequately measure the relevance of each criterion considering their interactions.

The principle of concentration of preferences [19] makes it possible to derive such capacity. This principle, consistent with aversion to uncertainty in the decision-making process, leads a decision-maker to seek the maximization of the ability to discriminate the most preferred alternative. It leads, in the case of determining capacities of sets of criteria, to assign greater importance to those sets that exhibit a higher ability to point to an alternative as the most preferred. The importance of criteria is related to the personal aim of the decision-maker to choose the best among the available alternatives, and, barring possible gross mistakes, high measurements provide more reliable information about differences in preference than low measurements do.

Assuming an absence of interaction, the principle of preference concentration allows for the use of weighted averages with weights indirectly extracted from the results of the application of the criteria to the alternatives. In this case, the weights will be proportional to the maximal probabilities. However, by allowing for interaction, the combination via the Choquet Integral provides a more general standard. In the opposite direction, assumptions of generalized additive independence and other forms of modeling relations among criteria [25] are even less restrictive, but, compared to such approaches, the Choquet Integral has the advantage of simplicity.

When interaction is assumed to be absent and weighting average of the preference probabilities for isolated criteria is performed, the global preferences still add to 1, while, when the preferences are combined via the Choquet Integral with respect to a nonadditive capacity, this sum can vary. Nevertheless, the possibility of interaction being present must always be considered.

When pairs of criteria are evaluated, instead of isolated criteria, if two criteria agree in giving high preference to an alternative, even if it is not the most preferred by either of them, their high joint preference for this alternative results in a high capacity for the union of the two corresponding unitary sets. The capacities of sets of more than two criteria are determined similarly.

Why does this construction suitably consider interactions? Interaction is present in the selection process if a choice of an alternative according to a given criterion either increases or decreases the effect of the preference according to other criteria. A preference criterion interacts with others in the selection of the best alternative if its inclusion in addition to the others in the evaluation process increases or reduces the probability that the best alternative will be identified.

The same applies to groups of criteria regardless of the reason for the influence. Such reasons may include exchangeability, complementarity, substitutability, or preferential dependence [26], but only the effect, not the origin, of the interaction needs to be established.

This application of the principle of preference concentration is similar to maximum likelihood estimation. It attributes to a criterion a capacity proportional to the preference value that this criterion assigns to the alternative to which it assigns the highest preference.

Finally, and more importantly in the search for standards, extracting information on preferences for criteria from available information about preferences for alternatives according to those criteria is simpler and more reliable than asking directly for information about the relative importance of the criteria in abstract comparisons.

Figure 1 highlights the benefits of the introduction in MCDA of the approaches advocated here.

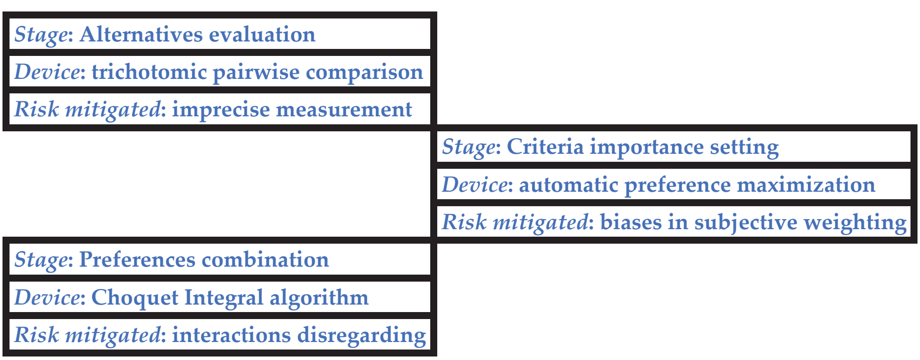

Figure 1. Benefits of the introduction of each of the approaches.

3. Results

This section presents a set of procedures that constitute standards for (i) calculating the preference probabilities according to each criterion, (ii) deriving the capacities of the sets of criteria, and (iii) ranking the alternatives by the Choquet Integral.

3.1. Standards for the Individual Assessments

The probability of preference for each alternative according to each criterion is obtained from evaluations by a sample of the population whose preference is to be measured.

Preference probabilities are derived from the values of the trichotomic pairwise comparisons that they produce.

The preference counts are transformed into probabilities by dividing the counts by the total number of evaluations. Let us denote by C_{ij} the count of preferences for the *i*-th alternative according to the *j*-th criterion and by $A(k, j, i, u)$ the result of the trichotomic comparison between alternatives *i* and *u* according to the *j*-th criterion by the *k*-th evaluator. This result has three possible values: 1 if the k-th evaluator declares *i* preferable to *u*, 0 if the evaluator declares u preferable to *i*, and $\frac{1}{2}$ if the evaluator declares indifference between *i* and *u*.

The preference count for *i* according to the *j*-th criterion, C_{ij}, is the sum

$$C_{ij} = \sum_{ku} A(k, j, i, u) \tag{1}$$

for *k* varying across all the raters evaluating according to criterion *j* and *u* ranging over all the alternatives that *i* is compared with.

This count is, therefore, the sum of the number of pairwise comparisons where *i* is preferred with half the number of comparisons where *i* is considered equivalent to another alternative. The estimate of the probability of preference for *i* is the quotient

$$P_{ij} = C_{ij}/C_j \tag{2}$$

of the count C_{ij} by the number of comparisons

$$C_j = K_j \cdot N \cdot (N-1)/2, \tag{3}$$

for K_j, denoting the number of evaluators by the *j*-th criterion, and *N*, the total number of alternatives.

The sum of these probabilities is exactly 1.

It is interesting to note that

$$A(k, j, i, u) = 1 - A(k, j, u, i), \tag{4}$$

granting antisymmetry.

However, the trichotomic pairwise comparison approach avoids the requirement for transitivity [27]. Transitivity need not hold, generally, in the evaluation of preferences. Consider, for instance, the case of ranking a group of tennis players when a criterion may be based on the observation of matches in some number of tournaments. In pairwise comparisons, the evaluator declares a player better than another by looking at the result of a match. It is possible to observe player i_1 beating player i_2, who beats player i_3, while player i_3 beats player i_1.

3.2. Standards for the Initial Joint Assessments

Once the preference probabilities according to each criterion have been obtained, the criteria capacities that will be used to combine these preference probabilities according to the individual criteria into a global score can be calculated.

Leaving aside the weighting of the criteria and the interactions between them, global scores can be obtained by using the preference counts to directly estimate the preference probabilities for each alternative. Extending the case of only one criterion, in the case of a set *J* of two or more criteria, a preference score P_{iJ} for alternative *i* according to *J* will then be obtained by adding the C_{ij} given by Equation (1) along the criteria *j* in *J*. To avoid implicitly overvaluing those criteria *j* with a large K_j, it will instead be employed thusly:

$$P_{iJ} = \sum_{j \in J} P_{ij}. \tag{5}$$

This initial assessment assumes additivity. Other forms of additive composition are described in [28]. They include probabilistic rules to obtain the preference according to at least one of the criteria in J. Assuming, respectively, the maximum dependence and independence between the indicators involved, P_{iJ} will be given by $max_{j \in J} P_{ij}$ or by $1 - \Pi_{j \in J}(1 - P_{ij})$. Nevertheless, counting is the easier form of evaluating the effect of joining the criteria.

These counts give all the criteria and all the experts equal importance, although weights can be included if there is sufficient information to consider the ratings differently by distinct criteria or by distinct experts. For instance, to control the effect of any factor unduly raising the preference according to some criteria, when translating the counting C_{ij} into the probabilities of preference P_{ij}, the importance of any criterion j may be corrected by applying a proportional reduction to the vector of probabilities of preference according to j (for instance, dividing all P_{ij} by K_{jj}).

3.3. Standards for Considering Interactions

A capacity on S is a nondecreasing function μ defined on the power set of S with values of 0 at ø and 1 at S. Capacities are not-necessarily additive measures that express, for each subset of S, the subjective importance associated with that subset.

Estimates of the capacities of the criteria can be obtained directly from the experts' evaluations. However, it is simpler to extract them from the preference counts.

Starting with the preferences according to each subset of criteria above denoted P_{iJ}, the principle of concentration of preferences leads to the measurement of the capacities as proportional to the vector of maxima along these preferences. The exact capacity values will be obtained by scaling such that a capacity of 1 is assigned to the set of all the criteria.

Formally, the capacity assignment algorithm for the subset J will have the central step of computing, along all the alternatives, the maximum of the joint preference probabilities

$$M(J) = max_i P_{iJ}. \tag{6}$$

The final value of the capacity is achieved with the final standardization that consists of dividing by the largest value. Thus, the capacity of J is

$$\mu(J) = M(J)/M(\mathrm{S}). \tag{7}$$

3.3.1. Simplified Capacities

In the case of a large number of criteria, the above derivation of capacities may be limited to sets with a small number L of criteria, while capacity 1 is assigned to all the sets of a larger size. That, is, while the sets of more than L criteria receive capacity 1, the sets J of 1, 2, … L criteria have the capacity given by

$$\mu(J) = M(J)/maxM(H) \tag{8}$$

for H varying along the sets of criteria of cardinality L.

This simplification may reduce the importance of the final score of criteria with strong interactions with large sets of criteria. To prevent distortions, computation for a few other small values of L is advisable if the scores for $L = 2$ do not present a clear preference for a best alternative.

3.3.2. Combination via the Choquet Integral

To consider in the global scores, in addition to the preferences between the criteria, the interactions between them, the preference probabilities according to the isolated criteria are combined via the Choquet Integral.

The Choquet Integral is a form of aggregation used in place of the weighted average when it is possible that interactions between criteria may invalidate the use of compensatory addition.

For any function $x = (x_1, ..., x_t)$, of domain S = {1, ... , t} and values in R^+, the Choquet Integral of x with respect to the capacity μ on S associates with x the non-negative real number

$$C_\mu(x) = \sum_{j \in S} \left(x_{\tau(j)} - x_{\tau(j-1)} \right) \cdot \mu\{\tau(j) , \ldots , \tau(t)\}, \tag{9}$$

for τ denoting a permutation of S such that

$$x_{\tau(1)} \leq x_{\tau(2)} \leq \ldots \leq x_{\tau(t-1)} \leq x_{\tau(t)} \text{ and } x_{\tau(0)} = 0. \tag{10}$$

The Choquet Integral is equivalently given replacing (9) by

$$C_\mu(x) = \sum_{j \in S} x_{\tau(j)} \cdot [\mu(Z_{\tau(j)}) - \mu(Z_{\tau(j+1)})] \tag{11}$$

for

$$Z_{\tau(j)} = \{\tau(j), \ldots , \tau(t)\}, \tag{12}$$

for all j from 1 to t, and

$$Z_{\tau(t+1)} = \varnothing. \tag{13}$$

When combining preferences via the Choquet Integral, one is also following the principle of concentration of preferences. In fact, the Choquet Integral assigns greater value to the highest preferences if they are obtained by applying a criterion with greater positive interactions with other criteria and lesser value otherwise.

To see how this happens, let us consider the case of only two criteria. If the interaction between the two is positive, the capacity (equal to 1) of the set of both criteria is greater than the sum of the capacities of each in isolation. Thus, the integral value is closer to the highest value than the arithmetic mean is. In fact, the integral is the sum of the smallest value and the product of the multiplication of the difference between the two values by the complement of that smallest capacity, and this complement is higher than the capacity of the second criterion if there is positive interaction and lower if there is negative interaction. In the weighted average, this complement would be replaced by the capacity of the second criterion.

4. Discussion

A discussion of the results is developed here based on the application of the proposed standards to two numerical examples.

4.1. First Example

Let us first consider a case of 100 alternatives evaluated based on four criteria. For illustrative purposes, this case may be thought of as a choice among 100 candidates for some position in a representative democracy. They are evaluated according to four criteria, which may be related to their commitment to objectives concerning fiscal balance, inducement of economic development, social action, and environmental protection, for instance.

Table 1 presents the preference counts resulting from the trichotomic pairwise comparison of the alternatives. The first 11 numerical rows present the counts for the first 11 alternatives, A1 to A11. The other alternatives, of smaller preference, have all the same counts shown in the last row. For the first two criteria, C1 and C2, the evaluations are obtained from three experts, C11, C12, and C13 for the first criterion and C21, C22, and C23 for the second criterion. The last two columns present unique counts C31 and C41 for the last two criteria, C3 and C4, possibly derived from comparisons of party platforms. The score 89 for A11 according to each criterion may be associated to this alternative being always evaluated as worse than the first 10 and better than the last 89, and the score 44 for the last 89 alternatives, from A12 to A100, may be associated to them being tied and evaluated as worse than the other 11.

Table 1. Counts of preference by criterion.

Alternative	C11	C12	C13	C21	C22	C23	C31	C41
A1	97.5	96.5	97	94	93.5	96.5	99	96
A2	97.5	96.5	97	94	98	96.5	96	97
A3	97.5	93	97	98	95.5	96.5	98	94
A4	97.5	96.5	97	96	98	96.5	94	95
A5	94	96.5	93	94	93.5	93	95	98
A6	94	96.5	97	98	98	96.5	93	93
A7	94	96.5	94	98	95.5	96.5	97	99
A8	92	91.5	91	91.5	91.5	91	90.5	91.5
A9	91	91.5	91	91.5	91.5	91	90.5	90
A10	90	90	91	90	90	91	92	91.5
A1	89	89	89	89	89	89	89	89
A12/A100	44	44	44	44	44	44	44	44

By dividing the count values by the total number of comparisons for each alternative, of 4950 for the last two criteria and three times that number for the first two criteria, the probabilities of preference for each alternative according to each criterion are obtained. Their values are shown in Table 2. For each column of probabilities, the sum of the values of the first 11 rows with 89 times the value of the last row is equal to 1.

Table 2. Probabilities of preference by criterion.

Alternative	C1	C2	C3	C4
A1	0.019596	0.019125	0.020000	0.019394
A2	0.019596	0.019428	0.019394	0.019596
A3	0.019360	0.019529	0.019798	0.018990
A4	0.019596	0.019562	0.018990	0.019192
A5	0.019091	0.018889	0.019192	0.019798
A6	0.019360	0.019697	0.018788	0.018788
A7	0.019158	0.019529	0.019596	0.020000
A8	0.018485	0.018451	0.018283	0.018485
A9	0.018418	0.018451	0.018283	0.018182
A10	0.018249	0.018249	0.018586	0.018485
A11	0.017980	0.017980	0.017980	0.017980
A12 a A100	0.008889	0.008889	0.008889	0.008889

In Table 3, it can be seen how the capacities change with the ceiling L. In Table 3, omitted is the capacity null for the empty set and 1 for the set of all four criteria.

Table 3. Capacities of the criteria by ceiling.

Criteria	L = 2	L = 3	Full
{C1}	0.494898	0.331435	0.250323
{C2}	0.497449	0.333144	0.251613
{C3}	0.505102	0.338269	0.255484
{C4}	0.505102	0.338269	0.255484
{C1,C2}	0.988946	0.662301	0.500215
{C1,C3}	1	0.669704	0.505806
{C1,C4}	0.989796	0.662870	0.500645
{C2,C3}	0.993197	0.665148	0.502366
{C2,C4}	0.998299	0.668565	0.504946
{C3,C4}	1	0.669704	0.505806
{C1,C2,C3}	1	0.993166	0.750108
{C1,C2,C4}	1	0.992597	0.749677
{C1,C3,C4}	1	0.997722	0.753548
{C2,C3,C4}	1	1	0.755269

It can be noted in Table 3 that, among the subsets of two criteria, the one with the highest capacity is formed by C1 and C3, which receives capacity 1 for L = 2. Notwithstanding, C1 is out of the set of three criteria with the highest capacity.

Table 4 presents the final scores.

Table 4. Final Scores for 3 capacities.

Alternative	L = 2	L = 3	Full
A1	0.079200	0.078661	0.078132
A2	0.078377	0.078156	0.078014
A3	0.078654	0.078243	0.077684
A4	0.078299	0.077788	0.077340
A5	0.077992	0.077452	0.076988
A6	0.078086	0.077117	0.076636
A7	0.079200	0.078842	0.078301
A8	0.073938	0.073889	0.073704
A9	0.073731	0.073530	0.073334
A10	0.074143	0.073765	0.073577
A11	0.071919	0.071919	0.071919
A12/A100	0.035556	0.035556	0.035556

In Table 4, it can be seen how the variation in the capacities affects the final decision. Evident is the highest preference for alternative A7, with a tie with A1 if the simpler capacity resulting from assigning capacity 1 to all the sets of more than two criteria is employed.

4.2. Second Example

As our second example, we consider a real case with a number of criteria that is both larger than usual and larger than the number of alternatives.

It is based on data from [29], of a study of failure mode and effects analysis (FMEA) in the nuclear energy industry. In that study, a hybrid approach to FMEA was designed to handle high-risk environments considering two human reliability dimensions of intelligibility and stress in addition to the classical FMEA dimensions of severity, occurrence, and detectability. This led to the consideration of a set of nine factors: severity of the impact on people (S), on the facilities (F) and on the environment (E), frequency of occurrence (O), undetectability (U), complexity (C), time to diagnosis (T), workload (W), and duration of stressful tasks (D). In [30], ten main modes of human failure following a failure in the external source of energy were identified, which characterized successive stages of risk control. They are summarized in Table 5.

Table 5. Modes of failure situations.

Mode of Failure	Situation
M1	align replacement generator
M2	manually activate water feed pump
M3	timely activate emptying tank prevention
M4	restore auxiliary feedwater system
M5	start bleed and feed
M6	close motorized isolation valve
M7	close manual valves
M8	establish safety injection
M9	start long-term refrigeration component
M10	align suction from containment well

In [29], these modes of failure were evaluated by a team of experts separately considering each of the nine factors. Here, instead, the aim is to employ the values of these evaluations to rank the nine factors. The idea is to obtain information useful for the development of risk management strategies based on the actions taken to control the factors to address the situations represented by the modes of failure.

The first step of this analysis is, then, the counting of pairs of factors with higher evaluation for each factor. The approximate measurements of [29] are presented in Table 6, and the results of the trichotomic counts for each factor according to each mode of failure, divided by the total of 36 comparisons, are presented in Table 7. As probabilistic preferences for the modes of failures according to the factors, the values in each column of Table 6 sum 1. The same is true for Table 7 since there the columns are filled by the vectors of measures of preference for the factors, which are then compared with reference to the modes of failure.

Table 6. Evaluation of 10 modes of failure according to 9 factors.

Mode of Failure	P	F	E	O	D	C	T	W	D
M1	0.09	0.08	0.08	0.20	0.07	0.06	0.05	0.09	0.09
M2	0.03	0.03	0.03	0.10	0.09	0.05	0.04	0.03	0.03
M3	0.27	0.06	0.08	0.08	0.11	0.05	0.05	0.27	0.02
M4	0.06	0.03	0.03	0.13	0.09	0.05	0.04	0.06	0.03
M5	0.12	0.23	0.16	0.08	0.09	0.08	0.05	0.12	0.09
M6	0.06	0.04	0.04	0.06	0.14	0.19	0.28	0.06	0.26
M7	0.12	0.08	0.08	0.08	0.11	0.25	0.23	0.12	0.21
M8	0.07	0.12	0.19	0.10	0.11	0.16	0.15	0.07	0.21
M9	0.06	0.15	0.16	0.06	0.09	0.05	0.08	0.06	0.02
M10	0.12	0.19	0.16	0.08	0.11	0.06	0.06	0.12	0.04

Table 7. Evaluation of the 9 factors according to the 10 modes of failure.

Mode of Failure	P	F	E	O	U	C	T	W	D
M1	0.17	0.10	0.10	0.22	0.06	0.03	0.00	0.17	0.17
M2	0.06	0.06	0.06	0.22	0.19	0.17	0.14	0.06	0.06
M3	0.21	0.08	0.13	0.13	0.17	0.04	0.04	0.21	0.00
M4	0.15	0.03	0.03	0.22	0.19	0.11	0.08	0.15	0.03
M5	0.15	0.22	0.19	0.04	0.10	0.04	0.00	0.15	0.10
M6	0.08	0.01	0.01	0.08	0.14	0.17	0.22	0.08	0.19
M7	0.13	0.03	0.03	0.03	0.08	0.22	0.19	0.13	0.17
M8	0.01	0.11	0.19	0.06	0.08	0.17	0.14	0.01	0.22
M9	0.08	0.19	0.22	0.08	0.17	0.03	0.14	0.08	0.00
M10	0.15	0.22	0.19	0.08	0.11	0.04	0.04	0.15	0.00

It can be seen, comparing Tables 6 and 7, that, if a factor contributes with a high value in the evaluation of a mode of failure, conversely, the mode of failure presents a high value in the evaluation of the factor, but this is not an absolute rule as the evaluations are, in both cases, relative to the whole set of alternatives. For instance, M9 provides the highest evaluation for E in Table 7, while M8 is the mode of failure with the highest evaluation by E.

The application of the composition by the Choquet Integral with respect to the capacities for the values of L from 2 to 9 and full use of the interaction indirect assessments generates the final scores in Table 8.

The analysis of Table 8 reveals factors E, related to the severity of the environmental impact, and O, occurrence, tied in the first position. E also ranks first for each of the five highest values of L, whereas O is the first for the other three. These factors are thus identified as the more relevant factors to be considered in the management of risks based on the mitigation of the factors. This is consistent with the classical three-dimensional FMEA analysis, which highlights severity and occurrence.

Table 8. Final scores for the 9 factors applying 9 capacities.

Factor	L = 2	L = 3	L = 4	L = 5	L = 6	L = 7	L = 8	L = 9	Full
P	0.01840	0.01736	0.01700	0.01648	0.01582	0.01544	0.01494	0.01422	0.01366
F	0.02222	0.02095	0.01925	0.01793	0.01702	0.01644	0.01561	0.01465	0.01408
E	0.02083	0.02037	0.02021	0.01917	0.01828	0.01763	0.01673	0.01570	0.01508
O	0.02222	0.02222	0.02047	0.01884	0.01785	0.01725	0.01650	0.01564	0.01508
U	0.01944	0.01852	0.01791	0.01716	0.01652	0.01615	0.01568	0.01518	0.01477
C	0.01944	0.01852	0.01762	0.01602	0.01490	0.01435	0.01364	0.01291	0.01247
T	0.02049	0.01829	0.01753	0.01646	0.01524	0.01467	0.01399	0.01305	0.01249
W	0.01840	0.01736	0.01700	0.01648	0.01582	0.01544	0.01494	0.01422	0.01366
D	0.02066	0.01933	0.01839	0.01685	0.01545	0.01441	0.01354	0.01262	0.01208

5. Conclusions

This article brings a new approach to MCDA based on the application of standard rules. A set of standards is proposed. Its validity is checked and its usefulness for practical situations of large numbers of alternatives and of criteria is demonstrated.

The combination of preferences based on multiple criteria can be achieved via the simple procedures developed here, which serve as standards for the analysis of complex decisions with a high degree of subjectivity. The simplest standards comprise the combination via the Choquet Integral, the consideration of the interactions between the criteria by assigning importance to the sets of criteria proportional to the highest preference that they assign, and the employment of trichotomic pairwise comparisons in the data collection.

The strategy for criteria evaluation proposed is designed to concentrate preferences. It is based on the information on preferences for the alternatives according to the criteria instead of on the direct comparison of the criteria.

The results of the application of these standards may serve as a basis for comparison with the application of any MCDA method recommended by the peculiarities of each case. Variations in the capacities, which may amplify the basis of comparison, were studied in practical applications, presenting consistent results.

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Review

Current Ice Adhesion Testing Methods and the Need for a Standard: A Concise Review

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Abstract: Ice accretion is a serious problem in cold climates, causing automobile and airplane accidents, as well as severe economic losses throughout various sectors. To combat these issues, many solutions have been developed, such as de-icing materials, which can delay or prevent the adhesion of ice to a surface through chemical, temperature, or physical means. To effectively assess the properties of a de-icing material, ice adhesion testing must be conducted, of which there are numerous types, each with their own characteristics. Unfortunately, the same material, tested with different methods, may provide very different ice adhesion values. This makes it difficult to properly characterize a material's de-icing properties and compare values across the literature. In this review, we identified the main ice adhesion testing methods and compared ice adhesion values for a particular material with different testing methods. We then discussed some of the main issues with current ice testing methods and identified some of the main factors that may affect ice adhesion values, namely ice quality and the use of a mold, which may significantly affect the final ice adhesion results. Finally, we proposed a new, simple standard testing method, in an attempt to eliminate some of the issues with current ice testing methods.

Keywords: ice adhesion strength; mechanical shear test; cone test; centrifuge test

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1. Introduction

Ice, snow, and freezing rain can cause numerous issues for individuals, governments, and industries, due to the accumulation of ice [1–4]. When snow and freezing rain accumulate on surfaces and adhere, countless problems can occur such as downed powerlines, automobile accidents, and air traffic delays or accidents [3,4]. In addition to lost time, the economic impacts of ice accumulation can be damaging, costing billions of dollars per year in damage and lost revenue for aerospace and insurance industries, as well as individuals [1–4].

To limit the amount of damage caused by ice accumulation, ice removal and prevention are required as mitigation methods. While various ice mitigation methods are currently available, such as the use of road salt, propylene glycol, or ultralow ice adhesion surfaces, ice often still needs to be manually removed [5–7]. Thus, surfaces with low ice adhesion properties have been developed by researchers worldwide to delay or prevent ice adhesion on a substrate, and many of these surfaces rely on super-hydrophobic polymeric materials to inhibit ice adhesion [8–12]. However, testing these materials to assess their effectiveness can be fraught with issues, as there is no one specific standard to test the ice adhesion properties of a material. As a result, numerous methods exist for testing the ice adhesion of modern anti-icing and icephobic materials, many of which have variables that can affect the consensus of a material's performance, as each research group may create its own custom ice testing apparatus [11–14]. In addition, determining an accurate ice adhesion strength of a material is difficult, making comparison among materials difficult. While the general agreement is that lower force values indicate better anti-icing performance of a material, a set standard to test ice adhesion is needed to verify material performance.

Previous reviews on ice adhesion testing, such as one by Rønneberg et al., gave a critical assessment of various utilized ice adhesion methods and noted several factors that may affect ice adhesion testing, such as the cooling rate, water impact velocity, humidity, and temperature [14]. The authors then suggested a standard ice adhesion method, based upon horizontal shear, to obtain the ice adhesion values of a substrate. Another review by Work and Lian, in 2018, raised several valid points regarding the various issues related to ice adhesion testing [15], including temperature, ice type, strain rate, and the effects of geometry on the interfacial stress concentrations, which are often overlooked in ice adhesion tests. The review article also noted that higher scatter was observed for mold poured ice, compared to impact ice for certain substrates [15]. Although these above reviews noted several key parameters that can affect the obtained ice adhesion, they did not consider the effects and interactions of the mold and the mold materials that are often used to contain the ice during static ice adhesion testing. These factors are important, as the mold is a significant part of the ice adhesion testing system because it is in direct contact with the ice during freezing. In addition, while Rønneberg et al. suggest a horizontal shear test as a standard, the exact mold requirements for the test were not specified [14]. Because mold materials may interact with, and affect, ice formation, crystallization, and the final properties of the ice [16,17], this review aims to bridge this gap by assessing the various techniques for testing ice adhesion, focusing on some of the challenges, issues, and advantages related to the use of molds in ice adhesion testing.

We also compare some of the most applicable testing methods that may serve as an ice adhesion standard for testing new de-icing and icephobic materials, and we propose a simple test method that minimizes some of the issues associated with current methods, building upon the standard proposed by Rønneberg et al. [14]. Our proposed standard stipulates metrics that were not previously considered, such as detailing a removable mold material for the test, the thickness of the substrate under test, and the material of the force gauge, to limit the interference of additional parameters on ice adhesion testing.

2. Ice Adhesion Testing Methods

Designing an ideal ice adhesion test or an ideal icephobic material is fraught with difficulty. For example, a study in 2019 by Irajizad et al. noted that, although various anti-icing materials and substrates have been proposed, many still cannot mitigate factors that can affect ice adhesion, and interfacial ice adhesion strength and long-term substrate durability may change after exposure to various environmental factors [18]. In addition, many new de-icing materials have difficulty retaining their low ice adhesion strengths after repeated icing-deicing cycles, therefore retesting these surfaces may result in different ice adhesion strength values [18]. Furthermore, the design of the ice adhesion experiment, which contains numerous factors, can also affect the ice adhesion strength values, as the ice detaches from them differently depending on the substrate. For example, sample thickness can add variability in the detachment mechanism of the ice, where normal stress dominates crack growth, while in very thin substrates, the normal force is essentially eliminated [18]. Therefore, when assessing ice adhesion testing methods, all of these factors have to be considered, especially the interactions between the ice and substrate, to obtain an ice adhesion value for a material. Therefore, these parameters and factors will be further discussed later on in this article.

While various methods exist to test ice adhesion on a flat surface, the vast majority can be classified into two main categories: direct mechanical testing and centrifuge testing. Mechanical testing is identified by its direct approach to dislodge the ice, and mechanical force is applied directly to the ice to free it from the material being tested [19–21], while in centrifuge tests, centrifugal force dislodges the ice from the material [19–25], utilizing indirect forces. While direct mechanical and centrifuge testing represent the majority of the research found in the current literature [11–15,20–24], additional miscellaneous tests have emerged that involve various apparatuses and methodologies, and these will be discussed separately in this review.

Mechanical testing can be further classified according to the four common direct methods, including horizontal shear test [10,25–35], vertical shear test [11,36], and tensile test [37–39], which are schematically depicted in Figure 1. Unlike centrifuge testing, mechanical testing can be conducted on stationary equipment, such as a tensile testing machine or a cold plate with a push rod [27,28,36]. As a result, the ice that dislodges using a mechanical testing approach is typically preserved and can be quickly assessed for surface irregularities [30,31,35]. By contrast, centrifuge testing typically results in the destruction of the ice sample, as it impacts the wall of the centrifuge testing chamber and is consequently destroyed [22–24].

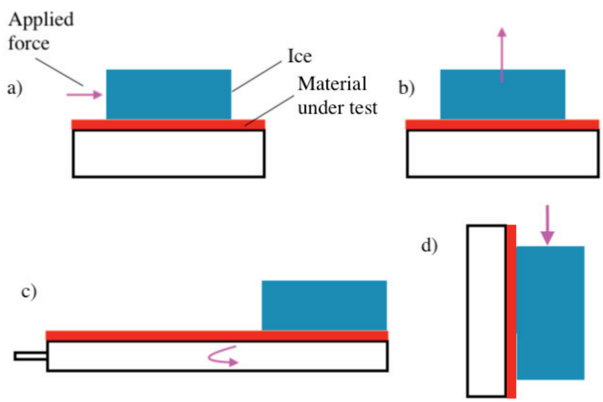

Figure 1. Schematic showing the four most common ice adhesion testing methods reported in the literature: (**a**) horizontal shear (push test), (**b**) tensile test, (**c**) centrifuge, and (**d**) vertical shear.

There are numerous challenges when testing ice adhesion, with the main issue being the environment in which the ice is created. Ice must be tested in an optimally cold setting but without the development of frost [3,5,6], otherwise the ice can melt or change its structure, which can invalidate the data. Furthermore, the method used to form the ice will significantly impact the final results, as ice structures will differ depending on the environmental conditions during testing [30,40–42]. There are various methods to form ice on a surface, such as a spray system [42] or using bulk water ice [27–36]. However, these different ice formation processes will generate different types of ice with different qualities, resulting in different adhesion strength values. Furthermore, two different fracture modes can occur during ice adhesion testing, adhesive and cohesive, depending on various parameters, including the substrate and the conditions during freezing [36–40]. Cohesive failure occurs when the ice itself fails or breaks, often leaving some ice on the substrate surface [36–40]. Adhesive failure, by contrast, is the failure along the ice and substrate interface, resulting in a clean break [36–40].

The literature on ice adhesion testing often differentiates between static ice (non-impact ice) and impact ice [3,4,14,15,27–38,42]. Static ice is typically formed by pouring water into a mold and allowing it to freeze in a specific structure or geometry [27–36]. By contrast, impact ice essentially creates freezing rain, which impacts the surface of the material and freezes [42], and these two methods will create vastly different types of ice and thus different experimental conditions [3,4,15,27–38,42]. Because impact ice is commonly used to assess aircraft ice accretion, it involves more complex factors than static ice [3,4,42–44]. In addition, the precise ice area can be difficult to control, such as during freezing spray experiments, where the ice can encompass a mock wing of an aircraft [42].

In real-life scenarios, ice will form on various structures, such as wind-turbines or the wings of aircraft, due to the accretion of moisture over time, from freezing rain, heavy fog, or snow [42]. Determining this type of ice accretion and accumulation is different from static (non-impact) ice. In impact ice, the water droplets are supercooled upon impact with the substrate, while in static ice experimentation methods, freezing of the ice is often gradual [15,30,36–42]. Although static ice testing methods do not directly mimic the real-life accumulation of ice on surfaces, they do offer a much more simplified and straightforward methods to determine the ice adhesion strength of a surface in an idealized laboratory setting. Thus, while spray experiments are closer to a realistic environment, and a valid method to determine ice accretion patterns on structures such as aircraft, they are not ideal for evaluating the specific ice adhesion value of a particular surface, as they may incorporate too many variables during experimentation, and precise ice formation cannot be guaranteed. As a result, static ice testing offers a more idealized setting for determining the ice adhesion strength of a material, which may be beneficial when assessing new materials development in a laboratory setting. Thus, to provide a simplified standard, this review focuses on testing methods involving non-impact or static ice adhesion, as it is a more controllable environment.

Ice adhesion, which occurs through hydrogen bonding at the molecular level with a surface [28], can be defined as the ratio of removal force over the area of the ice on the macroscale, following:

$$\tau = \frac{F}{A},$$

where F is the removal force over the area of the ice interface area, A [14,27–34]. To create ice with a specific ice interface area, a mold is typically employed to create an ice block with a defined area [26–35]. However, the presence of a mold can create its own set of issues, which will also be discussed later in this review.

Lastly, one of the main issues facing testing ice adhesion involves the ice itself. Ice is a brittle material, and the basic structure of the ice, and how it forms, will directly affect how it behaves [30,40,41]. This inevitably means that scatter will be included in the majority of the data, and multiple tests need to be carried out for each condition or coating material, to assess its ice-adhesion strength. Thus, not all ice is the same, and a comparison cannot be made between ice that is made using different methods or even under different conditions [14,15,40,41].

2.1. Direct Mechanical Testing

2.1.1. Tensile Tests

Tensile ice adhesion can be used to test adhesion by producing a mode I failure mechanism while the ice is encased in a mold. This method can, therefore, be unique compared to other methods, though this method still produces stress concentrations at the interface, between the substrate and the ice, resulting in a difference in the Poisson's ratio and Young's modulus [34,36].

One of the earliest tensile test methods was proposed by Rothrick et al., in 1939 [43], as a means of testing ice adhesion on aircraft. This method utilized two metal blocks, which were held together by ice and pulled apart to test ice adhesion strength. However, the authors noted that one issue was the failure of the ice itself in tension, rather than failure at the ice-metal interface [43]. Another method, proposed by Andrews and Stevenson, utilized a plane-strain-based tensile ice adhesion test with a polytetrafluoroethylene (PTFE) disc in a cylindrical mold, to induce a defect into the ice, resulting in mode I fracture failure of the ice [44]. Recent studies have also used this method to test the ice adhesion of ultralow ice adhesion surfaces. For example, Tetteh et al. tested a self-lubricating icephobic coating (SLIC) surface in a cylindrical chamber with a mold, using this modified tensile method with a Teflon coated disc to dislodge static ice, and obtained a tensile stress of 0.17 MPa for the SLIC material [38].

2.1.2. Direct Shear Testing

Push Test

Various shear ice adhesion testing methods have been developed, and shear testing is the most commonly used method due to its relative simplicity. Within the shear testing category, for non-impact ice, horizontal ice adhesion testing, the horizontal shear (also known as the push test) is the most common [26–35]. In this method, water is typically poured into a mold placed on the surface material subjected to test, and a force is applied either directly to the mold to dislodge the ice while encased in the mold, or the mold can be removed, and the force applied directly to the ice using a force probe [14,15,26–35]. The maximum applied force is then recorded, and ice adhesion strength is calculated by considering the cross-sectional area of the ice within the mold [26–35]. Numerous mold geometries and mold materials have been used, though some of the most common are rectangular or cylindrical glass, plastic cuvettes [26–34], or pipette tips [45]. The mold is filled with water, and the sample material is placed on top, frozen, and then, the entire system is inverted to perform the adhesion test (Figure 2) [26–34]. In addition, a bottomless cuvette can be used that is simply placed on the material and filled [46,47]. Shear testing also benefits from the use of a cold plate to cool down the substrate material directly, rather than the cooling of the entire environment, to freeze the ice [35].

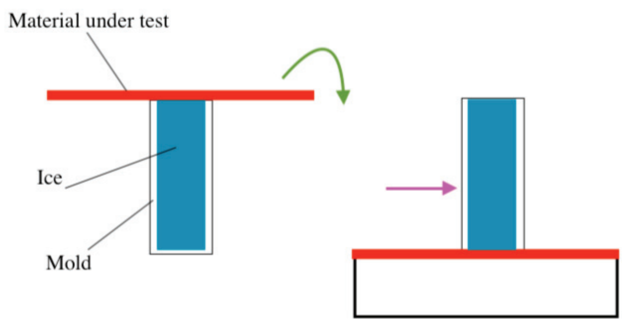

Figure 2. Schematic of horizontal shear test, where a plastic or glass cuvette is filled with water, placed in contact with a substrate, frozen, and then inverted to perform the test.

This direct shear, or push test method, has been commonly used to test novel super-hydrophobic de-icing materials, such as nano-textured superhydrophobic and lubricant-impregnated textured surfaces, as this method offers a simple surface for testing [26–35]. The ice can be directly placed in contact with the materials being tested without the need for additional steps, equipment, or setup. For example, Qian et al. used a bottomless cuvette to test a magnetically responsive lubricant-infused porous surface, where the deionized water was poured into the cuvette, frozen at −20 °C, with a placed probe in contact with the exterior of the cuvette, until the cuvette dislodged from the surface [30]. He et al. also used polypropylene (PP) tube molds, filled with water for 24 hours, to create ice cylinders and then, used a force probe to dislodge the tube-encased ice columns at a velocity of 0.1 mm/s [33]. Another variation on this method involves the vertical placement of the test apparatus, where the load cell pushes on the mold vertically, as displayed by Rønneberg et al. in 2019 [13]. In Meuler et al., glass cuvettes were used, with finely polished edges restricting the geometry of the ice at the edges, and each sample was frozen from the bottom up using a Peltier plate to reduce the stresses in the ice [48]. However, in the majority of studies utilizing the horizontal shear testing method, the force is applied directly to the exterior surface of a cuvette or mold, and not to the ice itself.

Other direct shear test methods include freezing a water droplet of a specific volume on the surface and pushing the water droplet with a small probe, as done by Ozbay et al. and Andersson et al. [49,50]. Ge et al. also pushed a frozen water droplet, using a horizontal probe at 1 mm/s to test and obtain the instantaneous shear force value, to determine the ice adhesion properties of an octadecyltrichlorosilane (OTS) superhydrophobic film [51].

Cone Test and Similar Methods

An additional shear test method was suggested by Haehnel and Mulherin [52,53], who proposed a 0° cone test to measure the ice adhesion strength of ice (Figure 3). In this setup, an inner cylindrical pin is contained within an outer cylindrical mold. The pin is then centrally inserted, with a notch at the bottom [53]. The mold can be coated with a material or substrate for testing, and then, the hollow area between the pin and the mold is filled with water, frozen, and the pin is pulled to test ice adhesion strength. Although this method commonly utilizes a tensile testing machine, the ice itself is put into shear [52,53]. Even though it is not as common as the push test method, it has been modified by other researchers, including Susoff et al. and Bharathidasan et al., who utilized modified zero-degree cone tests to assess various coatings [54,55].

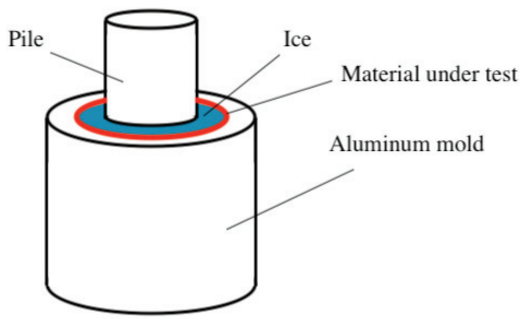

Figure 3. Schematic of a standard 0° cone test to measure ice adhesion strength.

2.2. Centrifuge Adhesion Test

Centrifuge testing to measure ice adhesion strength was developed as an alternative method to direct shear testing. The centrifuge adhesion test (CAT) was developed by Laforte and Beisswenger at the CIGELE laboratories, at the Université du Québec à Chicoutimi (UQAC), in an attempt to create a standard method for testing the ice adhesion strength of surfaces and substrates [56]. In this method, an aluminum beam (32 mm in width and 30 cm in length) is loaded with a test sample, 32 × 50 mm in size, with ice attached to one end of the beam [56]. The speed at which the ice dislodges is then recorded to calculate the ice adhesion strength [56].

The CAT apparatus can be used to measure the ice adhesion strength by applying a small amount of ice to a counterbalanced 300 rpm/s rotating aluminum beam, and ice sample preparation and formations were performed in a controlled cold environment at –10 °C [21,56]. An assessment by Rønneberg et al. in 2019, conducted over 126 experiments, tried to determine the detachment adhesion force, with the use of piezoelectrical sensor cells, to assess the impact speed of the ice [57]. In addition, three unique ice formations types were tested: silicon bulk-mold formed ice, multi-droplet impact ice formed by a wind tunnel, and water freezing precipitation ice formation [57]. However, the results were inconsistent, with a standard deviation of up to 28% [57]. Thus, while accepted common sample preparation generally follows the bulk-mold ice formation sampling, this can be a limiting factor when determining real-world ice formation on surfaces and structures such as transmission lines and aircraft wing leading edges [21,56,57].

2.3. Miscellaneous Test Methods

Other than direct shear and centrifuge testing, other miscellaneous tests have been developed throughout the years. A few of these methods, such as beam, peel testing, blister, and laser spallation, will be briefly described here, as examples of alternative miscellaneous ice adhesion tests.

2.3.1. Beam Testing/Bending

A simple 3-point or 4-point beam loading method can be performed on in-situ bulk-mold formulation fresh and sea ice, and the flexural (bending) strength resistance of ice behavior has been a research interest for the past half a century to determine beam loading forces of ice sheets in freshwater and seawater [58,59]. For example, several factors, such as temperature, columnar grain structure, sample size, and salinity, were considered during experimental testing conducted by M. Karulina et al. [58]. With over 1.5k tests, the researchers determined flexural strengths for freshwater ice fell between 0.275–0.807 MPa, and seawater ice was between 0.109–0.415 MPa [58,59], and salinity (soluble salts) present in the ice was also a key factor in ice flexural strength. Additionally, a previous study, conducted in 1989, indicated the importance of grain structure and isothermal temperature effects on fresh and sea ice beams, indicating higher flexural strength beams at < 0 °C and ice columnar grain orientation [59]. Experimentation on the bulk-mold formation of ice samples was extensively conducted. However, there is the possibility for testing analysis on low-density ice formation with varying masses that may provide comparable data for experimentation in the future.

2.3.2. Peel Test

Testing the surface ice adhesion strength of solid substrates can also be assessed using the peel method, though this method has not been thoroughly investigated in the literature. A NASA study, conducted in 1987, used two experimental methods to measure shear adhesion and peeling [60]. Peeling force measures were obtained in environmental conditions indicative to aircraft with the consideration of the different icing formation conditions. Although the shear strength of different ice formations varied between 0.28–0.34 MPa, with the highest strength at 0.83 MPa, the thickness of ice, densities, and adhesion to the substrate were not systematically determined [60]. Peeling strength values varied from 5.25–8.75 N/cm [60], and the authors noted that peeling strength was considerably lower with increasing peel angles on stainless steel and neoprene substrate material [60]. No additional data were provided to examine concentration stresses or validation of their experiments. However, it is possible the peel test provided limited single mode I failure results.

2.3.3. Blister Test

A blister test utilizes the metal shaft-loaded ice substrate interface to produce a crack propagation from a defined crack initialization area on the ice substrate layer. This test configuration is designed to measure the fracture energies over the various ice thicknesses and surface irregularities (roughness) [61]. Gluffre et al. analyzed the various mechanical surface fractures between an aluminum-plug impactor force on the ice sheet by using optical microscopy [61]. The experimental results produced stable crack propagation with a roughness of root mean square (RMS) value of 0.35–0.55 μm [61]. However, the fracture energies to initiate fracture in rough surfaces were unchanged, while smooth surfaces were shown to have somewhat lower average fracture energies [61]. Although rather inconclusive, this study's experimental configuration found surface irregularity and smoothness to be independent of fracture initiation with mixed failure modes.

2.3.4. New Ice Adhesion Testing Methods

One novel method for testing ice adhesion is laser spallation, which can be considered a modified version of the tensile test method. Saletti et al. also used laser spallation, which was adapted from the spalling test for polycrystalline ice, though this method has rarely been mentioned in the literature and though it provides a novel approach for ice adhesion testing [41]. In this technique, ice is encased in a mold and placed on a substrate surface. Then, a high energy pulsed laser is used to evaluate the tensile strength behavior of polycrystalline ice, by creating compressive stresses within the substrate [41]. These stresses propagate in the form of a tensile wave, at the free boundary, which impacts the ice and releases it from the substrate, providing an ice adhesion value. Archer et al. also used laser spallation to induce compressive stress waves, which acted as a tensile pulse on the substrate, removing the ice from the surface at a high amplitude [62].

With the increasing development of icephobic and de-icing materials using nanoscale fabrication techniques, determining ice adhesion strength at the nano and micro level is becoming increasingly important. In addition, ice adhesion strength testing at the micro- or nano-scale may offers more precise values, though it requires more expensive and complex equipment. For example, Matsumoto et al. used scanning probe microscopy (SPM) to test the ice adhesion strength of materials at the nano-scale level and found that ice adhesion values were higher values at the nanoscale level compared to macro-scale test results [63,64]. Building upon this, in 2018, Loho et al. used a novel nanoscratch technique to determine the ice adhesion strength of materials at the micro and nano level [65]. The researchers used a fluid cell tip made from Macor, a type of ceramic, to avoid thermal conduction and prevent the melting of the ice droplets during testing. The nanoscratch test consisted of three steps, where the fluid cell tip was moved up and over the sample, at certain increments [65]. During the nanoscratch, the tip was positioned 5 μm above the surface to measure sample tilt. Then, 150 μN of axial force was applied to the micro-nano sized water droplets, which were sheared off the substrate. The results demonstrated considerably higher ice adhesion values for stainless steel, compared to other shear tests.

3. Discussion

3.1. Issues with Current Ice Adhesion Testing Methods

Ice adhesion testing involves numerous factors, including the outside environment, the material or substrate being tested, temperature, the freezing rate, and the ice itself, which can change depending on a variety of factors under various experimental conditions, and can vary according to each test or experimental method. As a result, a tested substrate material, using different ice adhesion testing methods, may exhibit vastly different ice adhesion strength values. For example, as shown in Figure 4, the literature provides a range of possible ice adhesion strength values for uncoated aluminum surfaces, both polished and unpolished, between –9 and –15 °C, when tested using four different types of ice adhesion tests (laser spallation, direct shear, centrifuge, and tensile). In this particular example, ice adhesion strength values can encompass a large range, depending on the type of test, and even for the same material. Laser spallation had the largest value in this sample set, with a value of 180 MPa [62], while centrifuge testing exhibited some of the lower values (strengths), ranging from 0.42 to 0.24 MPa [13,21–25]. An even greater difference in values was found among the shear testing group, ranging from 4.5 to 0.11 MPa [38,39].

While some of these differences can certainly be attributed to the experimental conditions and variations in sample preparation, an identical material, tested in the same study but with two different methods, may also exhibit completely different values. For example, Yang et al. tested a bare aluminum surface at –8 °C using tensile and shear test methods and obtained ice adhesion values of 1.54 and 1.21 MPa, respectively [39]. Tensile testing can also result in two different fracture modes, adhesive and cohesive, depending on variables such as the substrate under test, the ice structure that formed during the test, and the exact placement of the PTFE disc location [39]. Thus, even identical materials may give entirely different results, depending on the test method. This makes it exceedingly difficult to compare ice adhesion values across the literature and verify and validate the anti-ice adhesion behavior of various new materials, as the testing method may greatly influence, and potentially skew, the resulting ice adhesion values. Centrifuge testing may be especially prone to these issues, and the failure mode may be difficult to discern, due to the speed of the test and the effects of wind before complete separation of the ice, which may act on the ice differently if there are slight variations in ice structure, shape, or texture.

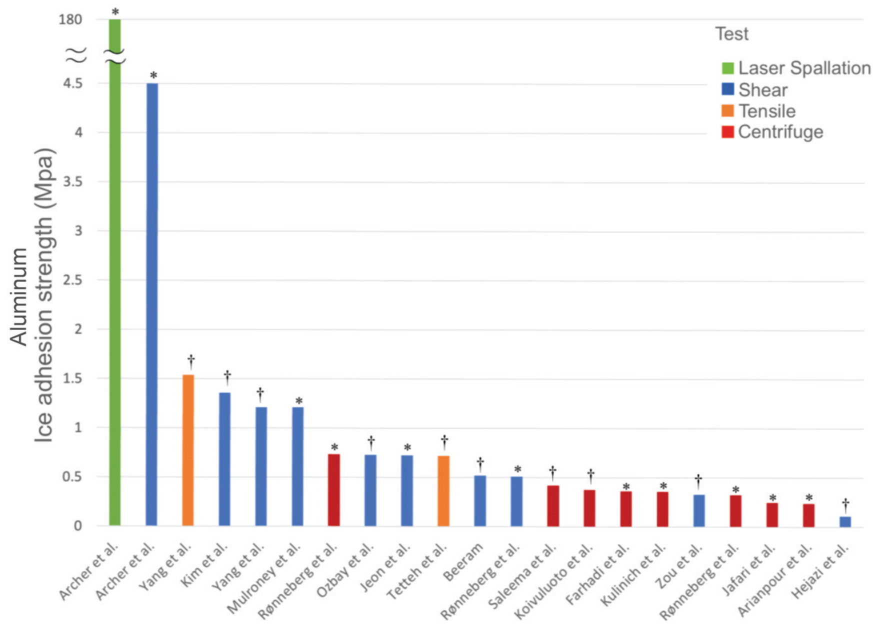

Figure 4. Ice adhesion strength values of an aluminum surface, tested using four different ice adhesion methods (laser spallation, direct shear, centrifuge, and tensile), between –9 and –15 °C. Data obtained from [13,21–25,38,39,49,62,66–72]. * Polished or mirror polished aluminum surface. † Bare aluminum surface, as-received, or otherwise untreated aluminum surface.

To determine some of the reasons for discrepancies in the aforementioned ice adhesion tests, various factors in the different test methods must be assessed. One possible source for variability is the mold that is used to hold and fabricate the static ice samples for ice adhesion testing. Molds appear to be a primary source of variability in the literature, as research groups currently use molds to contain various geometries, materials, and positions to contain the ice for ice adhesion strength testing [35,73]. In the most common test method, the horizontal push test, many studies have utilized plastic or glass cuvettes or pipette tips to form the ice, where the material being tested was placed directly on the cuvettes [21–34]. In addition, most of these molds could not be removed prior to testing, as most glass, and even plastic molds, are rigid and thus non-removable [35,73]. As a result, a few issues may occur, one of which is the lifting of the mold casing from the surface, due to the expansion of the ice as it crystallizes, forming a gap between the bottom edge of the mold and the material surface being tested, as shown in Figure 5a,b (red dotted circles) [73]. Consequently, when a force is applied to the exterior of the mold, as is often done in many of the horizontal and vertical shear tests in the literature, this gap may act as a crack initiation point [73]. Thus, the sample lifts from the substrate as the force is applied, and a wedge crack forms (Figure 6a,b) [73]. As a result, the force probe acts on the mold, rather than the ice itself, and the entire system, including the mold and the ice, are subjected to the test rather than just the ice itself. The gap between the mold and material under test will be detrimental to the test, as the ice will experience higher peeling forces under the action of shear, and these forces will occur on the side where the force is applied [68,73]. Therefore, displacement will occur not just in the x-direction (u_x) but also in the y-direction (u_y) [73]. Numerical analysis of this issue by Woll, in 2018, showed that this type of ice adhesion test can inherently cause rotation of the ice when pushed upon by a force probe [73], and this issue may also occur in cylindrical molds.

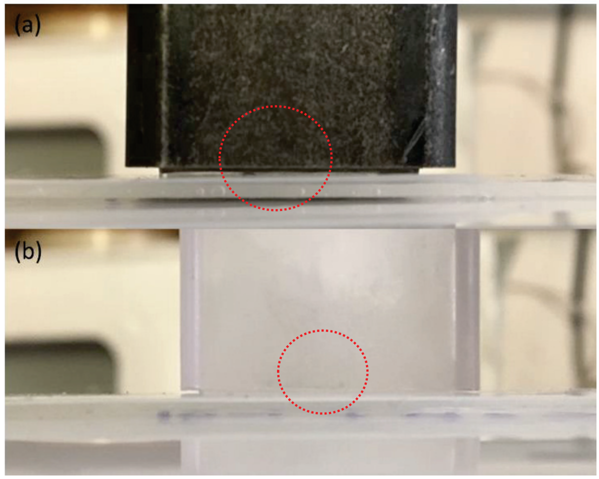

Figure 5. Bottomless rectangular steel (**a**) and polycarbonate molds (**b**) used for horizontal shear testing, with dotted circles showing the resulting gap that forms after freezing at –10 °C [73].

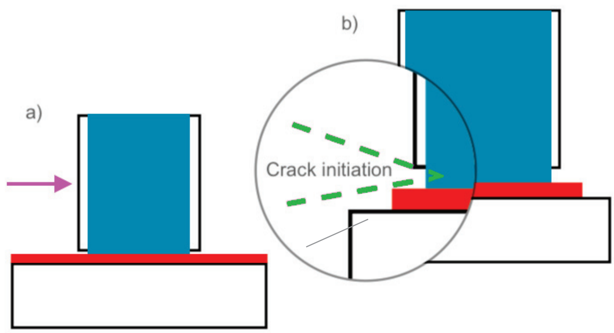

Figure 6. Gap between the mold and the substrate caused by the expansion of the ice during crystallization (**a**), and resulting wedge crack upon loading (**b**).

As a result, a horizontal shear test can become a multimodal test, rather than a pure shear test, resulting in a consistent failure initiation site that is detrimental to the determination of ice adhesion strength. Thus, the presence of a mold may increase the amount of rotation and result in artificially lower obtained ice adhesion values [35,73]. Subsequently, large disparities in ice adhesion values may occur.

Another factor is the material of the mold itself, which can significantly affect the quality of the ice, as well as the expansion rate of the ice, due to thermal effects of the mold such as heat transfer and heat capacity. The formation of ice and crystallization are affected by surrounding conditions such as temperature and atmospheric moisture, and under normal above-freezing conditions, liquid water molecules will continuously break and reform hydrogen bonds in a non-uniform fashion. However, upon freezing, the water molecules in ice become fixed, and the resulting ice crystal will form various shapes such as plates, dendrites, or columns, and the hexagonal arrangement of water molecules is the most common [17,18].

If the water is encased in a mold, the mold material may affect the ice structure, due to the instability at the mold/water interface [17,18], and the temperature difference from the chill zone to the center may result in a temperature gradient, ΔT. This temperature gradient can create variability in the liquid temperature of the supercooled area ahead of the liquid interface, causing ice crystal instability and dendrite formation [17,18]. Furthermore, if changes in heat occur, the liquid water may undergo crystallization instability, and the solidification process becomes dendritic [17,18], which can also affect ice adhesion strength values. Metal materials may be especially prone to equiaxed growth with different ice morphologies, causing thermal dendrites to form, due to their high thermal conductivity [17].

An ideal form of ice nucleation would be homogenous crystallization, where the ice shows no clear directionality [17,18]. However, for ice to undergo homogenous ice nucleation, the water would have to be free from any interactions with a mold or container surface, impurities (solutes), or other variables. Experimentally, this is nearly impossible to do, therefore nucleation and ice solidification more likely occur as a result of heterogeneous nucleation, where variables such as impurities in the water or a mold surface may affect crystallization and, consequently, ice stability. Interfacial stability can result in unstable ice structures, which can ultimately affect the ice adhesion strength when measured experimentally. In a cubic mold, dendrites will form with preferred growth directions, because the water in the mold center will be at a different temperature than the water that is closest to the mold, resulting in fine nucleated ice crystals at the mold surface [17,18]. This may especially result in directional dendritic patterns forming in molds made of metal or glass. As shown in Figure 7a–c, the metal mold (c) exhibits a highly directional dendritic pattern, the polycarbonate shows moderate distribution (b), while a silicone rubber mold shows the growth of ice without obvious directionality (a), by comparison.

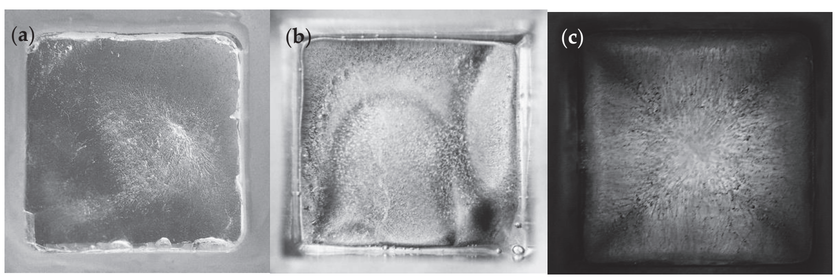

Figure 7. (**a**–**c**): Digital photos of ice forms in various bottomless cubic molds (**a**) silicone rubber, (**b**) polycarbonate, and (**c**) steel.

As a result, even under identical conditions, the mold material may result in lower ice adhesion values, for example, if a polycarbonate rather than a glass mold is used, even if the geometries of the mold are identical [35,73]. For instance, when geometrically identical steel and polypropylene molds were used to determine the adhesion strength of a polydimethylsiloxane (PDMS) substrate, vastly different values were obtained, 9.56 kPa and 13.86 kPa, respectively, even under identical test conditions [73]. However, when ice was formed in a removable silicone mold with the same surface area, removed, and then tested, the resulting ice adhesion strength was 24.06 kPa [73].

The above mentioned factors may be attributed to the differences in the cooling rate of the water as it crystallizes into ice, due to the differences in heat transfer rates of the dissimilar materials, and ultimately, this may cause ice with different brittleness qualities to form. Thus, ice that forms in a mold with a high thermal conductivity value, such as aluminum (~237 W/m·K), will have vastly different properties than ice made in a polycarbonate mold (~21 W/m·K) [17,18,73,74]. This effect may apply not just to a small cuvette or pipette type molds, but also to cylindrical cone tests, where aluminum molds are typically used. As a result, metal molds, due to their thermal conductivities, may create brittle ice that results in lower ice adhesion values upon testing, which has been shown to affect ice adhesion testing [17,18,35,41]. Therefore, if the quality of the ice is not controlled from one test to another, or even within the same test category, it can be difficult to obtain an accurate ice adhesion measurement.

Rønneberg et al. noted that, during various experimental setups, ice nucleation conditions can vary, as the rate of water freezing results in different ice densities [13,14]. This micro-structural freezing deviation has also been cited in other ice studies [15,17,18]. An indeterminate freezing density effect of water can alter the ice mass and thickness (volume) of the three types of ice samples. Mass density within tested ice samples can be uncertain; therefore, an undetermined density in combination with the variable thicknesses added uncontrolled variation in the experimental observation. The authors accounted for the systematic aberration to ensure data accuracy; however, the adhesion strength can be considered erroneous when comparing three different types of ice formation that differ in mass and thickness. Thus, in an ideal ice adhesion test, rapid freezing of the ice should be avoided. Irajizad et al. also noted the role of material thickness on ice adhesion, citing that, when assessing ice adhesion, the ice adhesion reduction factor is a critical metric for assessing the ice adhesion strength of substrates with a uniform thickness, and this factor is non-dimensional [18]. This consideration also adds complexity when determining ice adhesion values, as the force dominating crack growth may be different from one substrate to another, especially with advanced materials such as magnetic slippery surfaces (MAGSS) or other substrates that induce a liquid-to-liquid interface [18]. Thus, when considering the thickness of different materials, this factor should also be taken into account, to acknowledge the variability between samples due to the differences in crack growth. Maintaining a universal thickness among substrates could also address environmental erosion and loss of anti-icing properties, as some substrates that are thicker may delay material loss, or loss of properties. Therefore, to do a proper side-by-side comparison, uniform thickness for different substrates could help to eliminate additional variabilities.

Other methods that do not use a mold, such as the water droplet method, may also have issues due to their size and a surface adhesion area that is too small for comparison with other test methods. The overall surface area of the water droplet itself may also be too large, causing the water droplet to freeze too quickly. In these tests, the surface area is much greater compared to other tests, due to the small volume of water, and the crystallization rate of the ice may be difficult to control. As a result, controlling the freezing rate of the water, to create a standardized test, is just as critical as the test method itself.

Another factor is the thickness of the substrate material being tested. Especially for non-rigid materials undergoing a horizontal push test, peeling forces may be generated as the ice undergoes shear. This may increase with increasing thickness, and adhesion strength values may thus decrease with increasing substrate thickness, even for the same material substrate type. This may, again, be due to the vertical displacements that will increase as sample thickness increases. In addition, this may be especially pronounced in experiments where a mold is present, causing the mold to 'dig' into the substrate on the opposite side of the force probe, and this phenomenon may be especially pronounced if the substrate material is very soft [73]. As a result, thinner samples of soft materials will generate increased adhesion strength values, and when testing materials for ice adhesion, thinner substrates would be preferred over thicker substrates, to minimize this effect.

Lastly, in a shear test where a force probe is applied, the position of the force probe may affect the final ice adhesion values as well, due to the vertical displacements increasing with increasing probe height from the substrate surface. Therefore, a force probe that is too far (vertically) from the surface, may produce more torque, which will rotate the ice rather than produce pure shear [73]. Thus, to reduce vertical displacements, the force probe should be located as close to the bottom of the ice as possible, to minimize the development of vertical displacements, and avoid this issue.

3.2. Proposed Standard for Testing Ice Adhesion

There have been a few attempts to create a standard test to measure ice adhesion strength. In fact, the 0° cone test was proposed as a standard method for measuring ice adhesion in 1998, by Mulherin et al. [53]. Other attempts at commercial standardization have also been put forward, such as by Wang et al. who, in 2014, proposed a vertical shear test method using standardized commercial equipment [36]. However, these methods utilize non-removable molds, and thus contain some of the issues described above.

To resolve some of these issues, we propose a simple, standard horizontal shear test for testing anti-icing substrates and materials that do not require extensive setup or equipment, and a schematic of this test setup is shown in Figure 8. This test utilizes some aspects of the horizontal shear test, with a few modifications, in an attempt to prevent some of the issues that may arise from previous test methods. While Rønneberg et al. also proposed a simplified standard shear ice test in 2020, but the proposed test did not specify several factors discussed in this review, specifically the encasement of the ice in a mold, the type of ice that forms when in contact with a mold, the thickness of the substrate under test, or the material of the probe, all of which can interact with the ice and affect the resulting ice adhesion values [14]. Therefore, this standard improves upon previously suggested standards by eliminating some of the issues associated with ice formation when it interacts with an unsuitable mold material. This proposed method is intended to be simple, inexpensive, and accessible for the majority of substrates, while also reducing the number of variables that can affect ice adhesion strength.

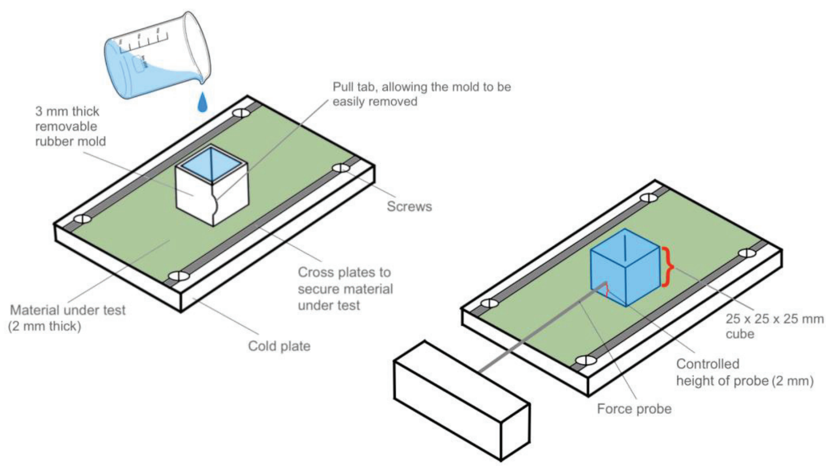

Figure 8. Proposed standard for horizontal ice adhesion testing, with the use of an easily removal one-time use mold.

In this setup, a 2 mm thick substrate material (to undergo ice adhesion testing) is secured to a cold plate at –10 °C with screws and two cross plates to properly secure the material to the system and prevent movement during testing. By maintaining a standardized thickness among all tested substrate materials, the substrate thickness effect would be minimized, and comparable values could be obtained. Maintaining a standard substrate thickness would also diminish the effect of the ice ‘digging’ into the substrate being tested. This is especially important for soft materials, such gels, which may exhibit different ice adhesion strengths depending on their thickness [73]. In addition, the cold plate below the substrate would provide a stationary location for freezing the ice on the surface, without the need for the system to be placed in a freezer, though environmental temperature and humidity should still be controlled.

A disposable cubic, 25 $\times$ 25 $\times$ 25 mm bottomless 3 mm thick non-stick silicone rubber mold could then be placed on the substrate surface. The mold would also feature a slit along the corner side, combined with an integrated quick-release pull tab, as shown in Figure 8. This slit, which would be joined with mild adhesive, would allow for the rubber mold structure to securely hold water while it freezes, but still allow for the mold to be quickly removed by pulling the mold apart at the slit. Of note, this design would be one-time use, as the adhesive would likely deteriorate after initial use. Nevertheless, by integrating a quick-release tab, the mold could be removed by peeling it off the surface of the ice horizontally, rather than forcefully pulling the mold upward. Traditionally, removing a mold can inadvertently push or pull on the ice if done incorrectly or too forcefully, affecting the adhesion of the ice, the bonding with the surface, or even causing the ice to melt. This is especially true for low ice adhesion surfaces. Therefore, handling the ice during or after crystallization should be minimized, as it can affect the ice adhesion results. Consequently, the mold must be easily removable with minimal impact, and this proposed design would reduce the handling of the ice after freezing.

The mold material type also offers specific benefits in terms of thermal properties, as rubber materials, including silicone rubber, offer low thermal conductivities (i.e., 0.16 W/m·K) compared to other materials, such as metal or glass [74,75], and are inherently non-stick and removable but still sufficiently stiff to ensure a uniform ice specimen. Therefore, the rubber mold material would minimally affect the development of the ice, creating less dendritic and more homogenous ice with fewer imperfections, as shown in Figure 7a. After water is added and frozen, this mold can be easily removed, leaving just the clear ice on the surface and eliminating the effect of a mold during the experiment. Furthermore, the use of distilled water would reduce the effects of solutes or contaminants on ice crystallization, which can cause the ice to undergo heterogenous ice nucleation.

A 2 mm diameter force probe, coated with a 1 mm layer of silicone rubber, is then placed 2 mm above the substrate, in direct contact with the ice. As mentioned by Loho et al., force probes that are metal may inadvertently interact with the ice, either by superficial surface melting if the outside environmental temperature is too high, or adhering to the ice, if the temperature is too low [65]. Therefore, by thinly coating the probe with a polymer coating, this effect may be minimized or prevented. In addition, by placing the force probe 2 mm above the surface, any vertical displacement effects would be minimized, such as torque, during testing [73]. Thus, the 2 mm probe placement allows for enough clearance for the substrate and is sufficiently close to the surface to minimize vertical displacements, but it also prevents the probe from dragging on the substrate surface. Lastly, a probe speed of 0.025 mm/s would dislodge the ice from the surface, while also preserving the ice for further analysis.

This test setup may also be helpful in preventing cohesive failure, as the ice would be more homogenous and less dendritic, and the location of the probe minimizes vertical displacements that may lead to undesirable results. Nevertheless, if metallic substrates were tested, dendritic ice would likely still form due to the interactions between the ice and the metal surface. However, directionality, due to the presence of a mold, would still be eliminated, thus offering a more representative ice adhesion strength value.

4. Conclusions

Ice adhesion testing is a complex process fraught with numerous variables, such as the environment, humidity, ice quality, and mold type. After considering and discussing several common ice adhesion testing methods, we proposed an ice adhesion testing system that is simple, cost-effective, and can be used in nearly any environment or laboratory setting. This test eliminates some of the main variables that can affect ice adhesion testing, such as mold surface interactions, heterogenous and brittle ice formation, substrate thickness variability, vertical displacements, and multimodal failure, thus creating a test that is as close to pure shear as possible. This method also avoids issues associated with other ice adhesion testing methods, such as tensile tests, which can result in failure of the ice itself in tension, rather than failure at the ice-metal interface. It preserves the ice, allowing for follow up analysis, unlike in centrifuge tests where the ice is destroyed. Ensuring ideal conditions for ice adhesion testing is difficult, due to the numerous factors that can affect the test. However, with our proposed test setup, more uniformity between tests may be achieved, allowing for better comparison among different materials, and potentially between different research groups. Therefore, while this method may not be ideal for all scenarios or experimental approaches, it may provide a more idealized environment for pure shear or horizontal ice adhesion testing. Furthermore, by eliminating some of the factors that may complicate testing, such as expensive equipment or non-removable molds, this method may provide a simple, yet feasible, approach for potentially achieving standardized ice adhesion testing in the future.

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Article

Developing Earthquake-Resistant Structural Design Standard for Malaysia Based on Eurocode 8: Challenges and Recommendations

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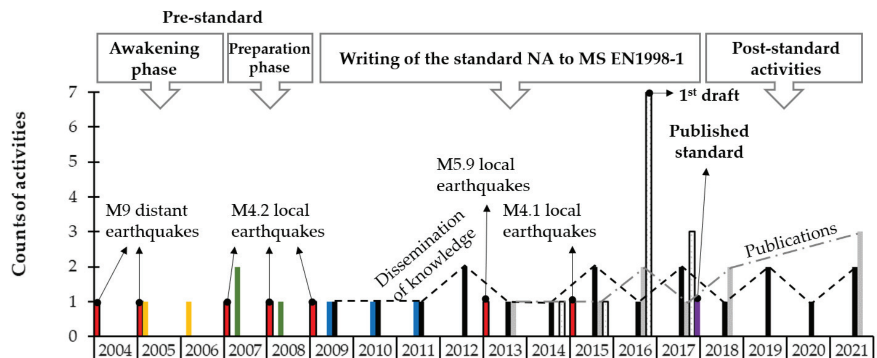
Abstract: In late 2017, the Malaysian National Annex (NA) to Eurocode 8 (EC8) was released and enacted following some 13 years of deliberations and preparations. The authors of this paper aim to use this article to share their experiences and reflections during this period of developing the first national standard for the seismic design of buildings for Malaysia. To begin with, there were major challenges in implementing the 20-year-old EC8 framework for a country so far away from Europe. The first challenge was adapting the probabilistic seismic hazard assessment (PSHA) methodology in a low-to-moderate seismicity region where the paucity of representative seismic data presented a great deal of uncertainties. To address this situation, imposing a minimum level of seismic hazard was recommended. The second challenge was about dealing with the outdated EC8 site classification scheme, which poorly represents the potential effects of soil amplification in certain geological settings. To address this situation, an alternative site classification scheme in which the site natural period is an explicit modelling parameter was introduced. The third challenge was concerned with difficulties generated by the EC8 provisions mandating Ductility Class Medium (DCM) detailing in certain localities where the level of seismic hazard is predicted to exceed a certain threshold. To address this situation, the viable option of using strength to trade off for ductility was recommended, or in cases where ductility design is needed, a simplified set of code-compliant DCM designs was presented. The fourth challenge was about handling the requirements of EC8 that the majority of buildings are to involve dynamic analysis in their structural design when the majority of practising professionals did not have the skills of exercising proper use of the requisite software. To address this situation, a generalized force method was introduced to control the use dynamic analysis in commercial software. It is hoped that, through sharing the lessons learnt, code drafters for the future would be able to find ways of circumventing the multitude of challenges with clear thinking and pragmatism.

Keywords: Eurocode 8; PSHA; site period parameterisation; DCM detailing; dynamic analysis; low-to-moderate seismicity regions

1. Introduction

Malaysia enacted its first national code of practice for the seismic design of buildings following the release of the Malaysian National Annex (NA) of Eurocode 8 (EC8, or officially named as MS EN1998-1) in late 2017 [1,2]. The authors were among the most active hands-on participants in the preparation of the standard since 2008. This paper is written to present the experience and reflections of the authors gained during this period of standard writing. To begin with, the authors encountered major challenges in the drafting of the NA for Malaysia where practising structural design professionals had no prior seismic design experience. This problem was compounded by the distance of Malaysia from the European continent. Whilst some of the challenges were presented briefly in a regional conference [3], this paper presents an opportunity to discuss the key issues elaborated.

There are many facets of activities that are related to the endeavour of standard drafting. To put the readers into context, Figure 1 presents a collated summary of the relevant key activities in chronological order since 2004. A detailed listing of the individual activities can be found in Appendix A. Broadly speaking, there were three phases in the development of the Malaysia NA to EC8 [2], namely, the pre-standard phase (of awakening and preparation), the standard-writing phase and the post-standard phase.



	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Seismic events	1	1		1	1	1				1		1						
Concern of engineers		1	1															
Setting up of standard writing committees				2	1													
Important initial publications						1	1	1										
Disseminations of knowledge						1	1	1	2	1	1	2	1	2	1	2	1	2
Documentations in publications										1		1	2	1	2			3
Major meeting/forum with stakeholders*											1	1	7	3				
Published standard														1				

*These are major meetings/forums. Frequent communications between group members took place throughout the whole process.

Figure 1. The roadmap of the drafting of the Malaysia NA of EC8 [1,2].

1.1. Pre-Standard: The Awakening and Preparation Phases (2004–2009)

Moderate size seismic events of magnitude 5 to 6 (M5–M6) occurring in Malaysia in the 1900s had been documented. The affected areas were mostly not so densely populated areas in Sabah (e.g., M5.3 in 1966 near Ranau, M6.2 and M5.7 in 1976 and 1994, respectively, near Lahad Datu). These early events had not drawn significant attention because of the sparse population in the affected areas where there were very few engineered building structures of significance. Memories of those events had faded away over time. However, there were also a few notable events, such as the Aceh M9.1–9.3 and Nias M8.6 megathrust subduction (interplate) earthquakes, which occurred offshore of Sumatra in 2004 and 2005, respectively. The epicentres of these earthquakes were at a far distance of about 600 km from Peninsular Malaysia, but many residing along the west coast of the Peninsular felt the shaking. Given the concern raised by the public, the Civil and Structural Engineering Technical Division of the Institution of Engineers Malaysia (IEM) took the initiative to write a position paper which was published in 2008 [4]. The position paper raised concern over the lack of preparedness of the Malaysian engineering industry in seismic design. Some short- and long-term measures to address the potential risks are recommended.

In 2008, IEM was appointed by the Department of Standards Malaysia as the standards-writing organisation for the Malaysia NA to EC8. Working Group 1 (WG1) was formed under a Technical Committee (TC) on Earthquakes to study the seismic hazard in Malaysia [5]. Whilst the initial focus was on distant interplate earthquakes generated from offshore sources, attention has also been drawn onto local intraplate earthquake events which had been recorded within the peninsular. Such events include the M4.2 earthquake tremor which occurred in 2007–2009 at Bukit Tinggi, which was about 30 km away from Kuala Lumpur, the capital city of Malaysia. The TC adopted the approach of addressing seismic risks holistically, and both local intraplate earthquakes and distant interplate earthquakes deserved an equal amount of attention.

1.2. The Standard-Writing Phase (2009–2017)

WG1 members acknowledged the challenges of dealing with seismic risks in a low-to-moderate seismicity region where representative locally recorded earthquake data were so lacking that undertaking seismic hazard assessments in a conventional manner would not be delivering any meaningful predictions. Hence, international experts in the low-to-moderate seismicity regions (the second and last authors of this paper) were invited to join the special study group under WG1 in June 2010. The first author was the candidate selected by WG1, trained under an apprenticeship program in grooming local talents for seismic engineering [5]. At a time when there was no existing ground motion model that could be applied to predict subduction earthquakes of mega magnitude (of the order of M9), the study put the focus on three key publications for the prediction of ground motions generated by distant interplate earthquakes [6–8]. Publications cited in the review laid the foundation of the seismic hazard study for Malaysia.

The main development activity was the drafting of the Malaysia NA to EC8 and was paralleled by sourcing input from international experts in the field, as well as working alongside local authorities and influential groups to resolve differences and to disseminate knowledge to local practising professionals through workshops and publications. All these knowledge dissemination activities have been conducted on a regular basis since 2009, long before the first draft of the national annex was presented for the first round of public comments in 2016 [9]. The standard-writing activities became most intensive in 2016. Around that time, the authors and co-workers travelled to different parts of Malaysia for various meetings, forums and discussions with stakeholders. These activities lasted until the standard was officially published in 2017 [2].

1.3. Post-Standard Phase (2017 to Current)

Standard writing is in itself a time-consuming activity. In addition, related work may be prolonged even after the standard is published as it is a natural continuation of obligations of the code drafters. In the case of the Malaysia NA to EC8, substantial knowledge dissemination activities are warranted to ensure that the intention of the standard is well understood by practising engineers. Hence, the authors (together with other local and international team members) have relentlessly dedicated themselves to achieve the goal of the standard following its release in 2017. A notable milestone was the setting up of a public access website (quakeadvice.org, last assessed on 28 October 2021) with free online lectures and software, which is aimed at educating engineers and guiding them into making proper use of the newly launched standard in a low-to-moderate seismicity region [10].

2. Technical Challenges Faced during the Drafting of the Standard

During the course of drafting the National Annex, the authors managed to gain highly valuable experiences, which are elaborated in this section. Four main technical challenges were encountered when implementing the EC8 framework into Malaysia. The first challenge was over the prediction of seismic hazards when representative data required for input into a probabilistic seismic hazard assessment (PSHA) were lacking. The second challenge was to do with the need to modify the outdated EC8 site classification scheme, which in its current form could poorly represent the conditions of the site in an earthquake.

The third challenge was to deal with EC8 mandating Ductility Class Medium (DCM) detailing in localities where the predicted level of seismic hazard exceeds a certain threshold. The fourth challenge was to deal with the requirement of EC8 to involve dynamic analysis of the majority of building structures when most engineers were not familiar with the requisite software. Each of these challenges, along with recommendations on how to best handle them, will be discussed in detail below under separate sub-headings.

2.1. Challenge 1: The Uncontrolled Use of Probabilistic Seismic Hazard Assessment (PSHA) Methodology

PSHA is a widely adopted seismic hazard modelling technique introduced in almost every textbook on earthquake engineering and seismic risk modelling [11]. The modelling methodology is perceived by many as being unbiased and scientific. When PSHA was first developed, it was intended for use in areas where data were abundant. In stable areas away from tectonic plate boundaries (i.e., intraplate regions), instrumented data are usually by far too inadequate to inform the spatial and temporal distribution of seismic activities. The use of aerial surveys to identify the location of active fault sources can be problematic because of the existence of blind faults (the location of which has been blurred by erosion or masked by sedimentary deposits). Seismic sources are usually represented as areal sources and are based on mapping the position of the epicentre of historical earthquakes. However, guidance is lacking on how to delineate the boundary of an areal source. Amid a lack of information and guidance, much can be left to the discretion of the operator of PSHA in addressing the unknowns. Thus, predictions derived from the same set of data can be non-unique. In an area where data are sparse, the modelled level of hazard in the vicinity of a historical earthquake would always be higher than before. This implied phenomenon of thePSHA as a predictive tool is an irony given that predictions so derived from it cannot be repeated over time [12]. The standard practice to resolve differences in opinion is to employ the so-called logic tree (decision making by "show of hands") procedure. This is another irony of the PSHA as a scientific procedure, as the outcome of the modelling is susceptible to influence by personal, commercial and political interests.

In EC8, the no collapse performance objective is based upon a recommended design return period (RP) of 475 years, which corresponds to a probability of exceedance of 10% in a 50-year design lifespan of a building. The concept of the Maximum Considered Earthquake (MCE) has not been incorporated into its underlying design philosophy, given that the code was drafted in the mid-1990s, at which time it was still the norm to design the majority of building structures for a return period of up to 500 years. Seismic design provisions around the world have evolved since that time. Notably, at present, there is a general consensus amongst earthquake engineers that an MCE event for normal buildings should have a RP of around 2500 years, which is consistent with a probability of exceedance of 2% in 50 years [13]. Importantly, structural designers operating in low seismicity regions are cautioned, herein, that the amount of increase in the ground motion intensity (corresponding to an increase in the RP from 500 to 2500 years) can exceed the default factor of 1.5 by a wide margin. A factor varying between 2.4 and 5 is predicted for intraplate earthquakes, as shown in Figure 2 [14–16]. As a result, designing a building to the no collapse performance limit state for a RP of 500 years would not in itself be able to offer the building adequate protection from the near-collapse limit state in an MCE. The trend of moving away from the conventional practice of designing to a return period of 500 years was initiated by the influential FEMA450 document [17] to guide the design of new buildings in the United States. The design seismic action was recommended based on an MCE of 2500 years scaled down by a factor of two thirds (reciprocal of 1.5). This scaling factor can be interpreted as the margin between the limit state of no collapse, and collapse prevention, in order that code-compliant buildings can always be assured of their ability not to collapse in a very rare earthquake event [18].

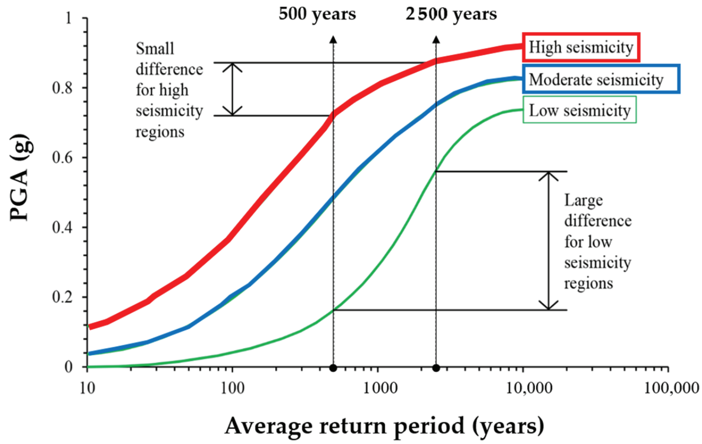


Figure 2. PGA-return period correlation with reference to low-, moderate-, and high-seismicity regions [14].

On recommendations made by WG1 in the draft Malaysia NA to EC8 for public comments [9], a minimum level of the reference peak ground acceleration (PGA) on rock (a_{gR}) of 0.07 g was considered to be specified for Peninsular Malaysia and Sarawak and 0.12 g for most of Sabah. The recommended minimum hazard requirements can be justified by referring to results from PSHA, assuming a uniform spatial distribution of seismic activities and observations on the frequency of occurrence of M > 5 earthquake events over an extensive area [19]. The a_{gR} value of 0.07 g and 0.12 g, as quoted above for a notional return period of 500 years, was two-thirds of the values (0.10 g and 0.18 g, respectively), corresponding to a return period of 2500 years, i.e., MCE [20]. The modelling concept as described is likened to that of background seismicity (which is a well-established concept). However, background seismicity models that have been employed in the past for PSHA did not prevent the value of a_{gR} to go as low as 0.03 g for a design return period of 500 years.

The requirement of a minimum seismic hazard design factor (Z, known as the effective PGA) of 0.08 for a return period of 500 years was implemented in the 2018 revision to the Australian Standard for seismic actions [21]. Thus, in most parts of Australia $Z = 0.08$ is specified in the new seismic hazard map, superseding an old model derived originally from conventional PSHA (based on information from documented historical seismic activities). In contrast to the new stipulation, the value of Z in the old map could be as low as 0.03 for areas where no historical activities had been recorded within the period of seismic activity observation. However, unlike the Australian Standard [21], recommendations in the draft Malaysia NA [9] for imposing a minimum seismic loading of 0.07 g and 0.12 g to different parts of Malaysia have not been taken up by the enacted version of the Malaysia NA to EC8 [2], which was completed through a decision process based on voting. One of the consequences of the decision is that an unacceptably low a_{gR} value of 0.04 g has been stipulated for Kota Kinabalu (the capital city of Sabah), which was only some 50 km from the epicentre of the M5.9 Ranau earthquake of 2015 (see Figure 3). In addition, given that the modelling has not been subject to any independent audit by a third party, the modeller did not have to abide by any rules nor any form of control. A small interval of 0.01 g PGA contour was created (as shown in Figure 3) even when such a high-resolution seismic hazard map cannot be justified (given that seismic data has only been recorded from one earthquake event).

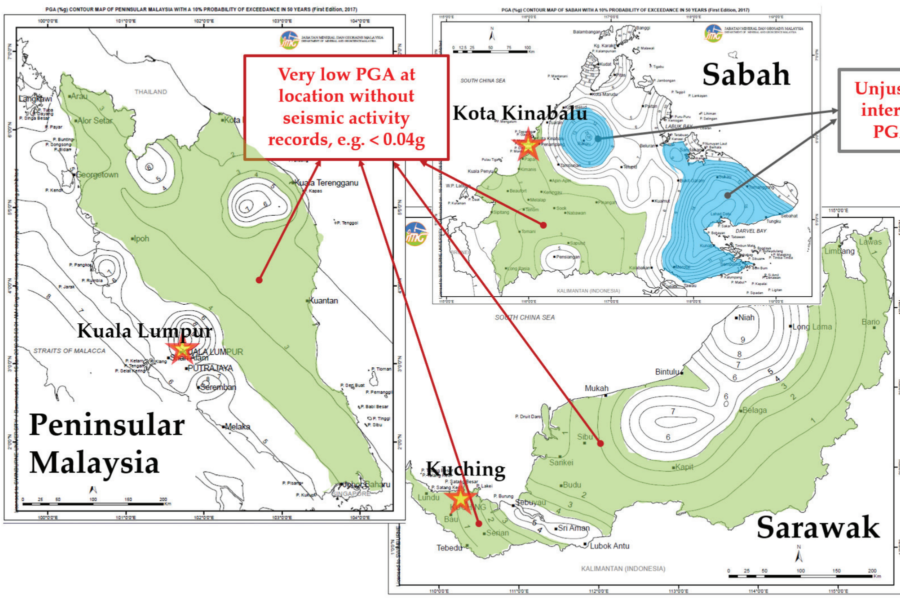


Figure 3. Challenge 1: The uncontrolled use of PSHA methodology in the enacted version of the Malaysia NA to EC8 [2].

The authors pledge all major codes of practice, including EC8, to require seismic hazard maps to be subject to proper auditing and to impose adequate minimum design requirements so that maps such as that shown in Figure 3 do not become part of a legal document for safeguarding the public. The authors recommended adopting a more robust model such as the one depicted in Figure 4. Although the recommended PGA values were originally 0.12 g for most of Sabah, the stipulated level of hazard has been harmonised to 0.11 g to have a smooth interval of 0.04 g across the country (i.e., minimum level of 0.07 g, intermediate level of 0.11 g and the highest level of 0.15 g).

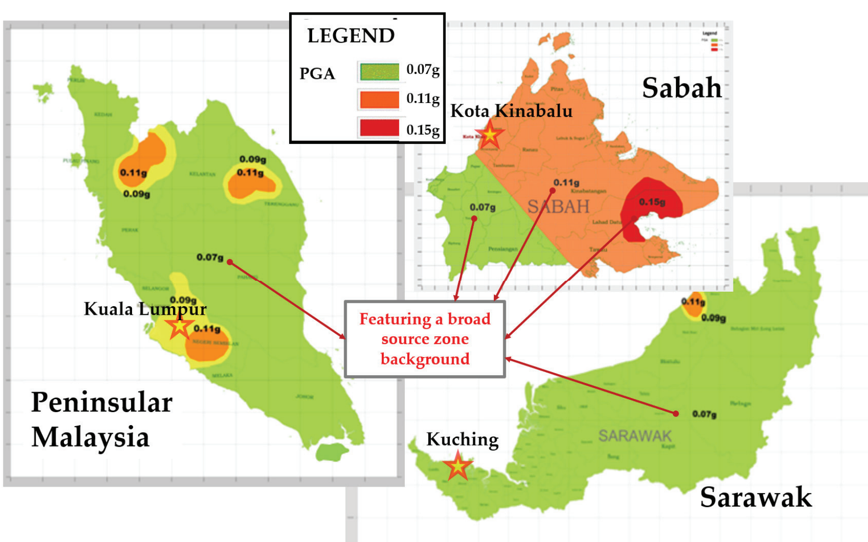


Figure 4. Proposed seismic hazard maps that circumvent Challenge 1.

2.2. Challenge 2: The Incomplete EC8 Site Classification Scheme

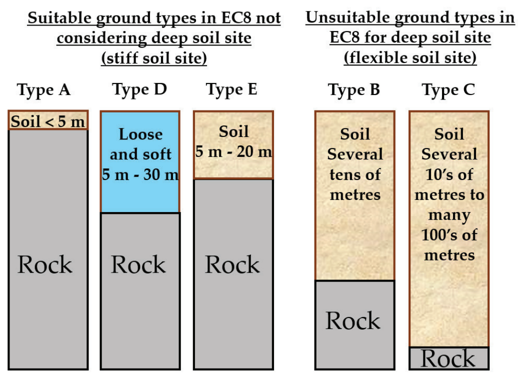
In EC8, a site can be classified into a few pre-defined site classes. Site effects are commonly related to a reference site class, i.e., ground type A for rock sites. The inability of this site classification scheme in EC8 to adequately address deep site geology is a matter of concern (see Figure 5). The potential occurrence of resonance can be particularly acute in buildings of limited ductility and more so on deep soil sites. The next edition of EC8 is to be revised to the form with site natural period parameterisation proposed in numerous publications by Pitilakis et al. [22–24]. The basis and justification for incorporating the site natural period as a parameter in the classification scheme and the effects of site resonance in the site amplification factor can be found in earlier studies conducted globally [25–28].

Table 3.1: Ground types in MS EN1998-1 [2]

Ground type	Description of stratigraphic profile	Parameters		
		$v_{s,30}$ (m/s)	N_{SPT} (blows/30cm)	c_u (kPa)
A	Rock or other rock-like geological formation, including at most 5 m of weaker material at the surface.	> 800	–	–
B	Deposits of very dense sand, gravel, or very stiff clay, at least several tens of metres in thickness, characterised by a gradual increase of mechanical properties with depth.	360 – 800	> 50	> 250
C	Deep deposits of dense or medium-dense sand, gravel or stiff clay with thickness from several tens to many hundreds of metres.	180 – 360	15 - 50	70 - 250
D	Deposits of loose-to-medium cohesionless soil (with or without some soft cohesive layers), or of predominantly soft-to-firm cohesive soil.	< 180	< 15	< 70
E	A soil profile consisting of a surface alluvium layer with v_s values of type C or D and thickness varying between about 5 m and 20 m, underlain by stiffer material with v_s > 800 m/s.			

-Unsuitable for deep soil site-

(a)



(b) (c)

Figure 5. Challenge 2: The incomplete EC8 site classification scheme. (**a**) Table 3.1 in MS EN19981-1 [2]. (**b**) Suitable ground types. (**c**) Unsuitable ground types.

A site classification scheme which incorporates the site natural period as a parameter was clearly much preferred to the then existing classification scheme of EC8 and was considered as the next generation classification scheme [22]. However, the transition to the new scheme had not occurred officially at the time when the Malaysian NA to EC8 [2] was drafted. It was decided that the NA adopted the (atypical) approach of having a dual classification scheme. The two schemes are, namely, Model A and Model B. This was purely a pragmatic decision to address political issues in the regulatory process. Model A can be used for shallow soil sites covered by soil sediments of thickness H_S not exceeding 30 m (Figure 5b), whereas Model B is mandatory for deep soil sites exceeding 30 m (Figure 6). The response spectrum associated with Model A was not stipulated by the main body of EC8 but was derived from analyses made by local investigators and was without justifications that have not been published in an international archival source. By contrast, Model B has a theoretical basis validated by site response analyses and field data from the 1994 Northridge earthquake [27,29–31]. As descriptions for the same ground type in the two classification models are totally different, code users can easily be confused. In comparison between the two models, Model B provides more accurate predictions of the real behaviour of a soil column in an earthquake. Model B is free of limitations in relation to the depth of the soil sediments, i.e., it can be applicable to soil sediments of any depth. Model B is recommended by the authors because of the deficiencies of Model A in covering for deep geology and more so where there is a distinct soil–rock interface.

Table A.1. Ground classification scheme in accordance to site natural period for soil deposit exceeding 30 m in depth in MS EN1998-1 [2]

Ground type	Description and range of site natural period, T_S (s)*
A	Rock site, or a site with very thin sediments and T_S < 0.15 s
B	A site not classified as ground type A, C, D or E
C	A site with sediments of more than 30 m deep to bedrock and T_S = 0.5 s to 0.7 s
D	A site with sediments of more than 30 m deep to bedrock and T_S = 0.7 s to 1.0 s
E	A site with sediments of more than 30 m deep to bedrock and T_S = > 1.0 s, or deposits consisting of at least 10 m thick of clays/silts with a high plasticity index (PI > 50)

NOTE. A soil site is characterised by its small-strain site natural period (T_S) of the soil layer down to the depth of much stiffer sediments or bedrock. For soil sediments of more than 30 m deep to bedrock, T_S can be estimated using the formula:

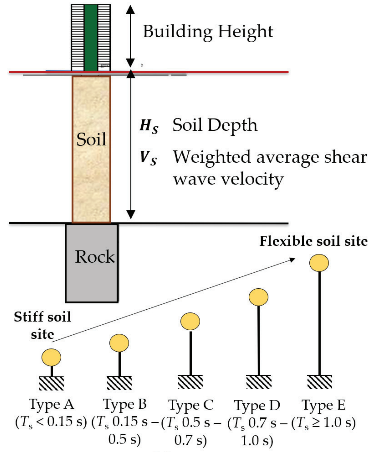
$$V_s = \frac{H_s}{\sum_i^n \frac{d_i}{V_{s,i}}}$$

$$T_s = \frac{4 \times H_s}{V_s}$$

The values of the site natural period (T_S), small-strain shear modulus or shear wave velocity (SWV, V_S) of soils can be measured by various geotechnical or geophysical testing techniques. Sedimentary layers with SPT-N value greater than 100 can be omitted in the computations of site natural period and weighted average, SWV.

Generally, two boreholes for a block of low-rise building are sufficient. Spacing of boreholes for multi-storey buildings should be 15 m to 45 m. More boreholes are necessary for problematic and erratic soil formation. The arithmetic mean of the site natural period T_S shall be adopted for site classification.

(a)



(b)

Figure 6. Solution to circumvent Challenge 2 with a new site classification scheme. (**a**) Definition for Model B from the Malaysia NA to EC8 [2]. (**b**) Analogy of stiff soil and flexible soil sites according to single-degree-of-freedom lumped mass oscillators.

With Model B, the rock–soil amplification ratio has its maximum value occurring at the site natural period (T_S). Figure 6a shows the five ground types as defined by the range of values of T_S. Apart from ground type A, which refers to rock sites (or very stiff soil sites), all other ground types refer to soil sites. Ground types A to E correspond to T_S values ranging from low to high, and with transitions at T_S = 0.15 s, 0.5 s, 0.7 s and 1.0 s, which can be viewed in analogy with a series of single-degree-of-freedom lumped mass oscillators model as shown by Figure 6b. The value of T_S is based on the conditions of small shear strains in the soil. The shear wave velocity (SWV, V_S) of soils can therefore be estimated based on geophysical or geotechnical measurements involving the use of Equation (1). The value of T_S can be taken as four times the travel time taken by seismic waves traversing the sedimentary layers overlying bedrock:

$$T_s = 4 \times \sum_{i=1}^{n} \frac{d_i}{V_i} = \frac{4H_s}{V_s}, \quad (1)$$

where d_i is the thickness, V_{i} is the initial SWV of the i-th soil layer, H_S is the total thickness of the soil layers and V_S is the weighted average SWV. Sedimentary layers with SPT-N values greater than 100 can be omitted in the computation of the site natural period and weighted average SWV. The authors proposed effective ways to choose the empirical equations to convert SPT-N to SWV [32] based on recommendations presented in a PEER report [33].

Model B has been reviewed and endorsed by Professor Kyriazis Pitilakis—current President (2018–2022) of the European Association of Earthquake Engineering (EAEE), who has been the Coordinator of the EAEE Working Group 6 on Geotechnical Earthquake Engineering, leading the future revision to EC8 concerning geotechnical matters [34].

In summary, site classification Model B was introduced to address the concern that the site response behaviour of deep soil sediments where the total thickness of the soil sedimentary layers overlying bedrock exceeds 30 m. The key feature of this classification model is the incorporation of the site natural period as the key modelling parameter. Model B is therefore generic in nature and is found on sound theoretical principles to emulate real response behaviour of soil sediments of different depths.

In a case study of a normal stiff soil site of 30 m depth (see Figure 7a) and a deep soil site of 58 m (see Figure 7b), the soil sediments had a common weighted average shear wave velocity of 222 m/s. The soil response spectra in both cases as obtained from the 1D site response analyses using STRATA [35] are presented in the format of Acceleration-Displacement Response Spectrum (ADRS) diagrams. It is shown that the proposed design response spectrum (DS) models adopted as Model B in the Malaysia NA to EC8 match the site response analysis results very well [31].

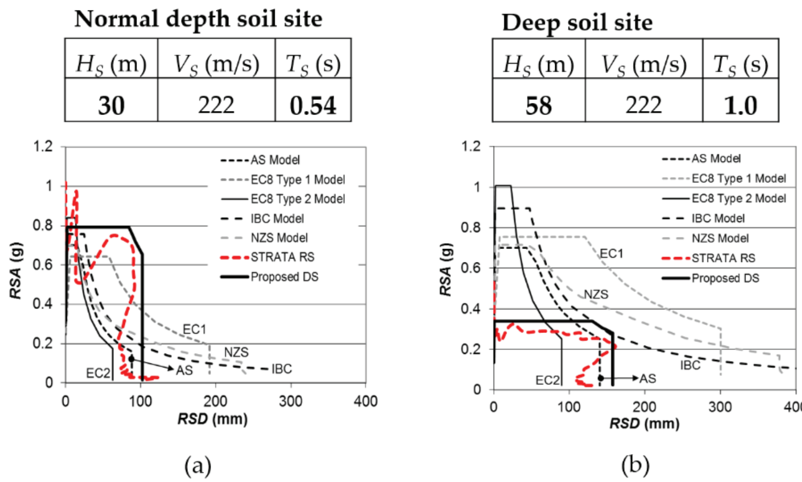


Figure 7. Proposed design response spectrum (DS) model based on Model B in the Malaysia NA to EC8 for (**a**) a normal 30 m depth soil site with T_S = 0.54 s and (**b**) a flexible deep soil site having the same weighted average shear wave velocity with T_S = 1 s [31]. The proposed model matches site response analysis results from STRATA [35].

2.3. Challenge 3: EC8 Mandated the Use of DCM Ductile Detailing for Higher Seismic Hazard Level

The third challenge was that EC8 had mandated Ductility Class Medium (DCM) detailing, which was about designing the structure to develop an inelastic response mechanism to dissipate energy in seismic conditions. This design approach is common in areas that are stipulated with a high level of hazard. EC8 recommended a set of pre-defined thresholds for very low, low and high seismic hazard levels as informed by Nationally Determined Parameters (NDPs). Introducing EC8 as an independent document instead of imposing seismic design provisions into various material standards was to make it easier for countries with a very low level of seismic hazard to opt out of adopting EC8 at all [36]. However, there has not been much guidance for regulators in low-to-moderate seismicity regions on how best to optimise the design and detailing requirements of building structures.

Figure 8a shows the concept of a force-based seismic design approach in which a behaviour factor (q-factor in EC8 [1]), or a similar set of factors, is introduced to lower the design strength of the seismic action whilst allowing the structure to experience post-elastic deformation in a ductile manner; the higher the level of ductility and/or overstrength, the higher the q-factor. Figure 8b shows the range of q-factor values recommended in EC8 according to ductility classes. Areas where the value of the design ground acceleration on rock (a_g, being the product of a_{gR} with an importance factor, γ_I) is lower than 0.08 g, or where $a_g S$ is lower than 0.10 g (where S is the soil factor), the condition of seismicity is classified as "low". Structures located in these areas can be designed to Ductility Class Low (DCL) in alignment with design compliance with the respective material-specific design standard. For example, structures built of reinforced concrete (RC) are designed to requirements stipulated by Eurocode 2 (EC2) [37], which is without any seismic detailing provisions. In areas where the hazard level is above the "low" threshold (including borderline cases, say a_g is 0.09 g), designers are compelled to comply with ductile design and detailing practices consistent with requirements in areas of high seismicity. This approach to seismic design may seem logical to some. However, the authors experienced major issues when implementing it in Malaysia.

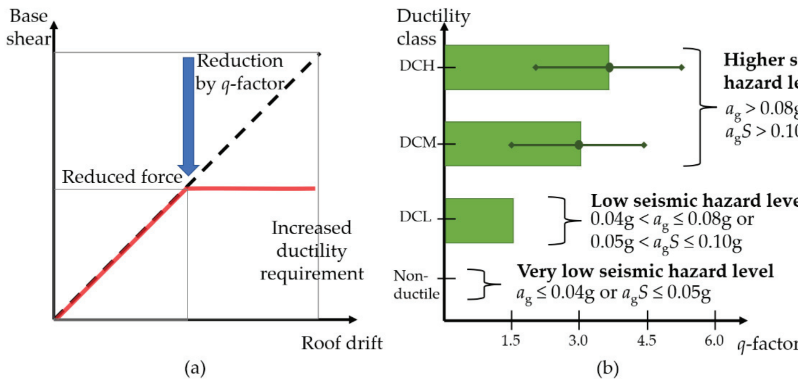


Figure 8. Challenge 3: The mandated use of DCM at the pre-defined threshold of seismic hazard level (**a**) the use of *q*-factor to trade-off strength with ductility in force-based methods (**b**) the pre-defined threshold in EC8.

In regions of low-to-moderate seismicity, such as Malaysia, practising engineers typically lack knowledge and experience in incorporating ductility into the design of a structure. The authors faced difficulties communicating the practice of ductile detailing (which was not the only viable way to counter seismic actions [38]) to the Malaysian engineering community in various seminars or events held for knowledge dissemination purposes. Dialogues with local structural design practitioners revealed the sentiment that DCM design should never be made compulsory, given that strength could be traded off with ductility. In the original draft of Malaysia NA to EC8 [9], which was prepared by the authors, building structures should have the option of adopting DCL irrespective of its location. This regulatory approach could be accomplished by altering the NDP for the low seismic hazard level so that no structure is compelled to be designed to DCM requirements (noting that DCH is overly complicated [38] and is only suitable for use in high seismic areas).

However, given the lack of justifications from the literature, the recommendations made by the authors in the original draft were challenged by a group of local investigators. As a result, the published Malaysia NA to EC8 [2] does not provide the option of adopting DCL for all building structures. Instead, the NA was to simply go by the recommended seismic hazard thresholds of EC8 when deciding if the design is to adopt DCL or DCM design and detailing. The authors strongly advocate improving current building design practices in low-to-moderate seismicity regions which are proliferated with structures lacking considerations of the performance of the structure in seismic conditions. However, linking the seismic hazard level of an area to ductile design classification is an outdated concept, gives little regard to local practices and is ineffective in ensuring a safe and sustainable built environment. Blindly imposing DCM design requirements would not deliver the desired outcomes.

The published Malaysia NA to EC8 [2] may result in many areas in the country being subjected to DCM design requirements. In anticipation of this challenge to engineering practice, the authors took the proactive initiative to assist practising engineers in coping with DCM design in RC buildings. Looi et al. [39] summarised the steps and developed EC8 DCM tools for rectangular RC columns (see Figure 9 for a snapshot) and RC shear walls (see Figure 10 for a snapshot). Designing RC columns and shear walls to DCM requirements requires determining the ductility demand (Step 1) and the associated confinement requirements (Step 2), which are to be compared against the confinement capacity (Step 3).

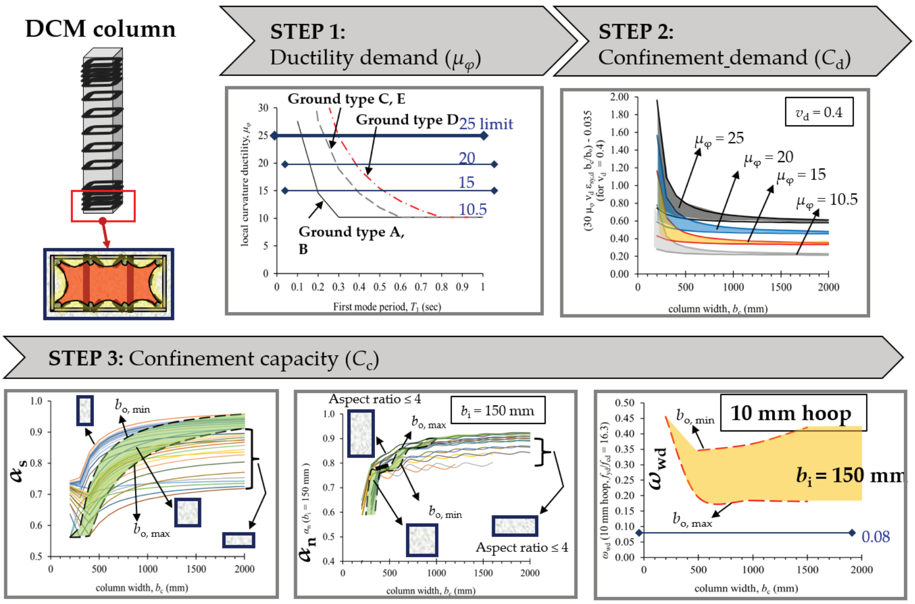


Figure 9. Developed DCM tools for rectangular RC columns to circumvent Challenge 3 [39].

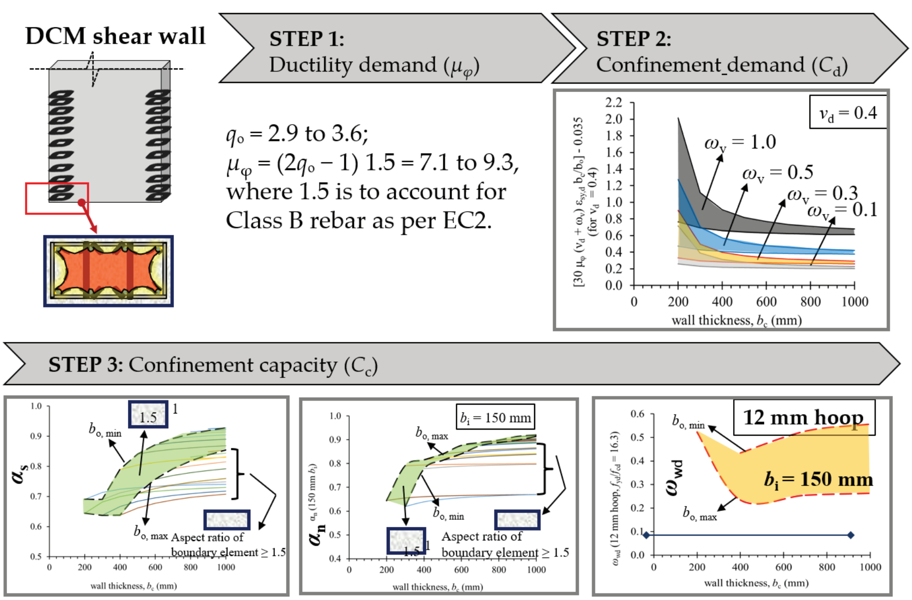


Figure 10. Developed DCM tools for RC shear walls to circumvent Challenge 3 [39].

A summary of the design recommendations is listed in Table 1. The length of the boundary elements is either 0.15 times the wall length or 1.5 times the wall thickness, whichever is higher. The rather complex and tedious confinement design procedure is hence circumvented. Interestingly, the presented design solutions are consistent with the draft provisions of the second generation of EC8 [40].

Table 1. Summary of recommendation for simplified DCM for RC buildings.

RC Elements	Parameters	Recommended Values
Beam	Depth	600 mm
	Hoop diameter	10 mm
	Hoop spacing	150 mm
	Longitudinal rebar diameter	20 mm
Rectangular columns	Size	500 mm × 500 mm
	Hoop diameter	12 mm
	Hoop spacing	150 mm
	Longitudinal rebar diameter	20 mm
	Longitudinal rebar spacing	150 mm
	α_n	0.78
	α_s	0.73
Shear walls	Thickness	400 mm
	Boundary length	600 mm [1]
	Hoop diameter	16 mm (or bundled rebars)
	Hoop spacing	150 mm
	Longitudinal rebar diameter	20 mm
	Longitudinal rebar spacing	150 mm
	α_n	0.80
	α_s	0.70

[1] The confined boundary element length has not considered the confined compression zone x_u at ultimate curvature estimated from equilibrium.

EC8 has imposed what is widely perceived as strict and complex rules for RC design and detailing. Preparing a full-fledge DCM based design calculation could be a daunting task to many engineers practicing in low-to-moderate seismicity regions. To circumvent around this challenge to Malaysian engineers, the authors have developed simple deemed-to-comply rules for achieving DCM compliance for the seismic design of RC beams, columns and shear walls. Meanwhile, it was revealed from past experimental research on RC columns [41,42] and RC shear walls [43,44] that deformability was severely degraded in conditions of high axial compression. Practitioners are urged to control the amount of axial compression on RC members irrespective of confinement provisions for ductility.

2.4. Challenge 4: EC8 Imposes Modelling of Irregular Buildings for Dynamic Analysis

EC8 provides a code-based lateral force method to emulate seismic behaviour by applying equivalent static forces to the building. However, this code-stipulated simplified analysis method is subject to stringent pre-qualification criteria which are concerned with vertical and horizontal regularity. Most of the building stocks in Malaysia feature irregularities in planning, such as asymmetrically disposed structural walls around the building, resulting in a significant eccentricity of the centre of rigidity from the centre of mass of the building. This form of irregularities can be compound with other forms of irregularities such as setbacks, discontinued load paths and transfer structures. EC8 prohibits the use of the lateral force method on a building that possesses any of these irregularity features. EC8 stipulates three-dimensional (3D) dynamic analysis (or modal response spectrum analysis) as the default analysis procedure. Executing dynamic analysis in a controlled manner requires expertise and experience in structural dynamics, and such engineering skills can be scarce in a country where seismic design practice has yet to be established. This type of challenge in Malaysia is common to other countries of low-to-moderate seismicity. To circumvent the challenge, the authors have devised a simple and yet accurate method of structural analysis (referred herein as the Generalised Force Method, GFM) that can be applied to multi-story buildings featuring horizontal and vertical irregularities. A key feature of GFM is that it does not rely on any code-based empirical formula to predict the natural period of vibration of the structure. The GFM may be applied at three different levels depending on the building (see Figure 11): GFM-1 is suitable for use in the 2D analysis of low-rise buildings; GFM2 has been enhanced to handle taller buildings, as higher mode effects have been taken into account (whilst generalised mode shapes and default modal period ratios are made use of to eliminate the need of modal analysis); and GFM3, which is structured into three tiers (Quick, Refined or Detailed methods), has been enhanced further to handle 3D phenomena [45]. Interested readers are recommended to read into recent publications presenting the GFM [45–47].

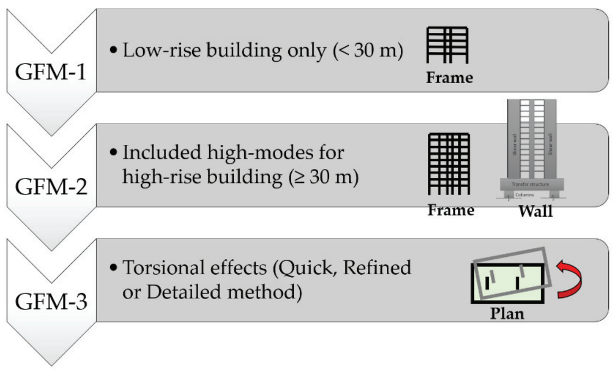


Figure 11. GFM methods to check dynamic analysis results.

The GFM has been demonstrated to provide reliable predictions on the deflection behaviour in buildings, including high-rise buildings and torsion-sensitive buildings (see Figure 12). GFM can be used as a tool to benchmark results generated by the computer in order to exercise control over the use of commercial software in undertaking complex analyses and to enable the design engineers to gain better understanding of the seismic response behaviour of the building.

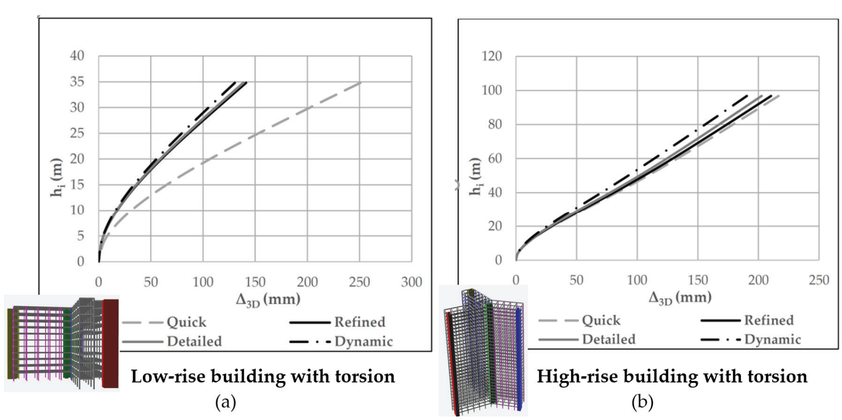


Figure 12. Validated examples of displacement profiles using the GFM methods: (**a**) asymmetrical low-rise building (**b**) asymmetrical high-rise building.

3. Future Outlook of the Second Generation of EC8 and Beyond

Standard drafting can be very time-consuming and baffled by many challenges. Take EC8 as an example: The first version was published in 2004 following a gestation period of nearly 20 years [48]. Revision to EC8, which is still underway, has been discussed in a few publications [36]. The second generation of EC8 was originally expected to have been concluded around 2020 [48] but had to be postponed to the end of 2021 and, subsequently, postponed further to 2022 (noting that its release is affected by the schedule of releasing a few related codes) [38]. Several key features in the revision as reported in the literature are summarised as follows [36,38,48]:

1. The number of NDPs is reduced by harmonisation, and this requires international consensus among the European member states.
2. The second generation of EC8 aims to improve its clarity by simplifying clauses and removing rules with limited practical utilities (i.e., overly "academic" provisions). For instance, the dependence on ductility classes to the level of seismicity is under review. The conditions of low-to-moderate seismicity areas require special considerations [38]; the number of ductility classes is consolidated from three to two [36,38]; the use of two spectral shapes Type 1 and Type 2 is to be abandoned [38]; the soil classification scheme and the associated site-factor models are to be revised [22–24]; methods of analysis for handling irregularities in buildings are also under review [38].
3. Research findings to fill the voids of knowledge and include introducing new methodologies for handling post-tensioned buildings, flat slab buildings and high-strength concrete.
4. Allow changes to evolve gradually. Engineers who have been trained to operate with the existing version of EC8 should not have much difficulty adapting to the new version. On a separate note, earthquake engineering is a fast-evolving discipline (e.g., the use of conditional mean spectrum [49] and risk-targeted hazard spectra [50] with the considerations of community resilience [51]). Hence, the EAEE has set up a working group entitled 'Future direction for EC8' to oversee the long-term development of EC8 through establishing broad guiding principles that are in alignment with the latest development and to gradually phase out outdated practices which are founded on technologies developed as far back as the 1990s or earlier [52].

4. Conclusions

This paper aims to record important milestones achieved by the authors and co-workers, who have been engaged for over a decade in developing the first seismic design standard for Malaysia in the form of a NA to EC8 [1,2]. NDPs were introduced in EC8 to resolve differences where consensus could not be reached amongst the European Commission member states during the drafting of EC8 [36]. Ironically, the authors encountered similar challenges as consensus over the NDP of the nation could not be reached. In addition, four major technical challenges stemming from outdated clauses in EC8 and their lack of fit for use in a low-to-moderate seismic environment were highlighted, discussed, and critiqued. A few key challenges have been brought up for detailed discussions, as summarised below:

1. There was a lack of control in applying the PSHA methodology to areas with a paucity of representative and reliable seismic data. To address this situation, imposing a minimum level of seismic hazard was recommended.
2. Areas typified by limited ductile building construction can be susceptible to soil-structure resonance, and more so on deep soil sites [31]. A conventional site factor model, such as that stipulated in EC8, would not cater for resonance conditions as described. An alternative site classification scheme in which the site natural period is an explicit modelling parameter was introduced.
3. The regulatory approach of mandating DCM ductile detailing requirements following the level of seismic hazard of the area (as shown on the seismic hazard maps) is an outdated practice. The viable option of using strength to trade off for ductility was

recommended. In addition, a simplified set of code-compliant DCM designs for RC columns and walls has been developed by the authors to circumvent the need to apply the complex design procedures as stipulated by EC8.
4. Amid the proliferation of commercial structural analysis software, EC8 mandates the use of dynamic analysis in the design of the majority of buildings. Dynamic analysis necessitates engineering skills and experiences that are scarce among engineers in Malaysia and other low-to-moderate seismicity regions. GFM methodology was introduced by the authors to exercise control of the use of commercial software avoiding the "black box" syndrome.

The future development of EC8 has been actively discussed in the literature in recent times [38]. Some of the new features are interestingly aligned with recommendations by the authors in relation to the four challenges discussed in this paper. The authors concur with the view that an effective standard should feature stability, simplicity and harmonisation [36,38,48]. Hence, it is also hoped that the next generation of EC8 contains well-defined provisions, free of grey areas and overly constrained clauses. Future developments of regulatory control for seismic design in low-to-moderate seismicity regions need to be approached in context with existing structural design practices in these regions.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. The details of the chronological activities from 2004 to current year 2021 in the writing of the Malaysia NA to EC8.

No.	Events	Location	Year	Remarks
1	Sumatran subduction M9 earthquake	Acheh, Indonesia	2004	Seismic event (1)
2	Sumatran subduction M8.6 earthquake	Nias, Indonesia	2005	Seismic event (2)
3	IEM Civil and Structural Technical Division's position documents	Kuala Lumpur	2005–2006	Concern of engineers in Malaysia
4	Sumatran subduction M8.4 earthquake	Bengkulu, Indonesia	2007	Seismic event (3)
5	IEM appointed by Department of Standards Malaysia to be the Standards Writing Organisation (SWO) for NA to EC8.	Kuala Lumpur	2007	Initiation of standard writing
6	IEM set up a Technical Committee (TC) on Earthquakes and established Working Group 1 (WG1)	Kuala Lumpur	2008	Setting up TC and WG for standard writing

Table A1. *Cont.*

No.	Events	Location	Year	Remarks
7	Local M4.2 seismic activities detected	Bukit Tinggi, Selangor	2007–2009	Seismic event (4)
8	A journal paper "Seismic load estimates of distant subduction earthquakes affecting Singapore" in *Engineering Structures* [6]	-	2009	Important publication (1)
9	Two-Day Course on Earthquake Resistant Design and Analysis of Buildings and Structures	Kuala Lumpur	2009	Dissemination of knowledge (1)
10	A journal paper "Ground-motion attenuation relationship for the Sumatran megathrust earthquakes" in *Earthquake Engineering and Structural Dynamics* [7]	-	2010	Important publication (2)
11	Symposium on Earthquake Ground Motions and Responses of RC Buildings	Kuala Lumpur	2010	Dissemination of knowledge (2)
12	Two-Day Course on Analysis and Design to EC8 Demystified	Kuala Lumpur	2011	Dissemination of knowledge (3)
13	An article "An Approach for Seismic Design in Malaysia following the Principles of Eurocode 8" in the *IEM JURUTERA Monthly Bulletin* [8]	-	2011	Important publication (3)
14	Sequel to Two-Day Course on Analysis and Design to EC8 Demystified	Kuala Lumpur	2012	Dissemination of knowledge (4)
15	Two-Day Symposium and Workshop on Earthquake Engineering in Malaysia and Asia Pacific Region	Kuala Lumpur	2012	Dissemination of knowledge (5)
16	Local M4.1 seismic activities detected	Temenggor Lake, Perak	2013	Seismic event (5)
17	An article "Recommended Earthquake Loading Model for Peninsular Malaysia" in the *IEM JURUTERA Monthly Bulletin* [53]	Kuala Lumpur	2013	Documentation in publication (1)
18	Two-Day Symposium and Workshop on Earthquake Engineering in Malaysia and Asia Pacific Region	Kuala Lumpur	2013	Dissemination of knowledge (6)
19	Two-Day Workshop on Recommended Earthquake Loading Model in the Proposed NA to EC8 for Sabah, Sarawak and Updated Model for Peninsular Malaysia	Kuala Lumpur	2014	Dissemination of knowledge (7)
20	IEM meeting and Standard writing workshop	Kuala Lumpur	2014	Major meeting/forum with stakeholders (1) *
21	Two-Day International Seminar and Workshop on Presentation and Reviewing of the Draft Malaysia NA to EC8	Kuala Lumpur	2015	Dissemination of knowledge (8)
22	IEM meeting and Standard writing workshop	Kuala Lumpur	2015	Major meeting/forum with stakeholders (2) *
23	Two-Day Course on How to Utilise Our Proposed EC8 Malaysia NA to Our Practising Consulting Engineers	Kuala Lumpur	2015	Dissemination of knowledge (9)
24	Special issue "Developing Malaysian Design Standards for Earthquake Resistance" in *IEM JURUTERA Monthly Bulletin* [54]	-	2015	Documentation in publication (2)
25	Local M5.9 earthquake	Ranau, Sabah	2015	Seismic event (6)
26	Kota Kinabalu, Sabah Town Council, mandated seismic design with PGA of 0.12 g	Kota Kinabalu, Sabah	2015	Interim enforcement of seismic design
27	Special issue "Public Safety in Earthquake Event" in *IEM JURUTERA Monthly Bulletin* [55]	-	2016	Documentation in publication (3)

Table A1. *Cont.*

No.	Events	Location	Year	Remarks
28	IEM Standard meeting to go through the public comments	Kuala Lumpur	2016	Major meeting/forum with stakeholders (3) *
29	A journal paper "Minimum loading requirements for areas of low seismicity" in *Earthquakes and Structures* [19]	-	2016	Documentation in publication (4)
30	Dialogue on The Proposed NA to MS EC8 on Design of Structure for Earthquake Resistance	Kota Kinabalu, Sabah	2016	Major meeting/forum with stakeholders (4) *
31	Special meeting with Sabah seismologist/geologist	Kota Kinabalu, Sabah	2016	Major meeting/forum with stakeholders (5) *
32	Draft Malaysian EC8 NA for public comments [9]	Kuala Lumpur	2016	Major meeting/forum with stakeholders (6) *
33	WG1 meeting with Department of Standards Malaysia (DSM)	Shah Alam, Selangor	2016	Major meeting/forum with stakeholders (7) *
34	National Consultation of the Draft Malaysian EC8 NA by DSM	Shah Alam, Selangor	2016	Major meeting/forum with stakeholders (8) *
35	Seminar on Analysis of Torsional Actions in Buildings	Kuala Lumpur	2016	Dissemination of knowledge (10)
36	WG1 study group meeting with Minister of Science, Technology and Information	Kota Kinabalu, Sabah	2016	Major meeting/forum with stakeholders (9) *
37	A journal paper "A design spectrum model for flexible soil sites in regions of low-to-moderate seismicity" in *Soil Dynamics and Earthquake Engineering* [31]	-	2017	Documentation in publication (5)
38	Special four seismic experts meeting	Kuala Lumpur	2017	Major meeting/forum with stakeholders (10) *
39	Two-Day Workshop on Proposed Seismic Analysis Methods for Regions of Low to Medium Seismicity	Kuala Lumpur	2017	Dissemination of knowledge (11)
40	A conference paper "Intricacies of addressing distant and local earthquakes in Malaysia in the official design standard EC8 Malaysia NA" at AEES 2017 [56]	Australia	2017	Documentation in publication (6)
41	Finalised Malaysian EC8 NA for public comments	Kuala Lumpur	2017	Major meeting/forum with stakeholders (11) *
42	Publication of MS NA EN 1998-1: 2015 (2017) [2]	-	2017	Published standard
43	Public forum on Malaysia NA to EC8 by DSM	Shah Alam, Selangor	2017	Major meeting/forum with stakeholders (12) *
44	A journal paper "Seismic Hazard and Response Spectrum Modelling for Malaysia and Singapore" in *Earthquakes and Structures* [20]	-	2018	Documentation in publication (7)
45	Two book chapters in *Guideline on Design of Buildings and Structures in Low-to-moderate Seismicity Countries* [46,47]	Hong Kong	2018	Documentation in publication (8)
46	Two-Day Symposium on Earthquake Resistant Design of RC Buildings based on the EC8 Malaysia NA: From Loading Characterisation to RC Detailing	Kuala Lumpur	2018	Dissemination of knowledge (12)
47	Two-Day Symposium on Earthquake Resistant Design of RC Buildings based on the EC8 Malaysia NA: From Loading Characterisation to RC Detailing	Kuching, Sarawak	2019	Dissemination of knowledge (13)

Table A1. *Cont.*

No.	Events	Location	Year	Remarks
48	A conference paper “The Malaysian Seismic Design Code: Lessons learnt” at NZSEE 2019 Pacific Conference on Earthquake Engineering (PCEE) [3]	Auckland, New Zealand	2019	Dissemination of knowledge (14)
49	Launching of www.QuakeAdvice.org website (last assessed on 28 October 2021) [10]	-	2020	Dissemination of knowledge (15)
50	One-Day webinar on Online Tools for Earthquake Resistant Design of RC Buildings based on the EC8 Malaysia NA	Malaysia, Australia	2021	Dissemination of knowledge (16)
51	A journal paper “Fast Checking of Drift Demand in Multi-Storey Buildings with Asymmetry” in *Buildings* [45]	-	2021	Documentation in publication (9)
52	A journal paper “Site-Specific Response Spectra: Guidelines for Engineering Practice” in *CivilEng* [32]	-	2021	Documentation in publication (10)
53	4-half day webinar on Analysis and Design of Building Structures for Seismic Environment in Malaysia	Malaysia	2021	Dissemination of knowledge (17)
54	A conference paper “Simplifying Eurocode 8 Ductile Detailing Rules for Reinforced Concrete Structures” at 17th World Conference of Earthquake Engineering [39]	Sendai, Japan	2021	Documentation in publication (11)

* These are major meetings/forums. Frequent communications between group members took place throughout the whole process.

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standards

Article

Benefits of Quality Management Standards in Organizations

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Abstract: The main motives for implementing standards are external and internal. External motives are related with aims to enter new markets, export new goods, meet customer requirements, achieve better corporate image, gain market share, or increase customer satisfaction. Internal motives occur when the organization itself wants to improve the internal system and when processes and benefits depend on the internal motives of the organization. In order to disclose the benefits of quality standards, an empirical study was conducted with quality representatives from organizations in different fields of business activity in Lithuania. The research aimed to investigate what quality management systems prevail in organizations and to reveal the motives and benefits of implementation. The empirical study found that after the implementation of quality management standards (QMS), the quality level improved; the number of incidents and defects (complaints) decreased; employee involvement and perception of quality increased; company profits increased; customer satisfaction increased; and company management was improved.

Keywords: standards; quality management; implementation motives; benefits of standards implementation

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1. Introduction

Standards play an important role in a globalizing world, both in terms of quality of life and in economic terms; however, the implementation of standards in organizations remains a delicate topic. There are still no full answers to questions regarding products, provision of services, how an organization is affected by quality systems, how standards can benefit an organization, and what added value is created by complying with standards. Consequently, the aim of the research was to reveal what kind of motives and benefits create the implementation of quality management standards for organizations today and to evaluate if there are any changes compared to previous research studies.

The research proved that the list of main motives and benefits for implementing quality management standards in organizations remains the same as it was revealed by previous studies: *motives* remain as a demand/pressure from the customers, while organizations want to increase market share or improve the quality of their product/services. *Benefits* in organizations are reflected by a decreased number of incidents, improved profitability, processes, procedures, etc.

The research also identified *motives not mentioned in previous studies*: (a) organizations could not operate their business without relevant standards or (b) organizations aimed to increase operational efficiency. *New benefits* appeared through management—after the QMS implementation, it became easier to manage organization, and operational efficiency increased.

2. Literature Review

The main motives and benefits of implementing quality management standards are external and internal [1]. External motives arise organically, when organizations aim to enter new markets, export new goods, meet customer requirements, achieve a better image, gain a larger share of the market, or increase customer satisfaction. Internal implementation motives occur when the organization itself wants to improve its internal system and processes [2]. Received benefits depend on the organization, and if standards are implemented solely based on external motives, there may be no significant benefits at all. Benefits are far greater when quality standards are implemented to increase the efficiency of the structure, systems, and processes of the organization [3].

Internal motives, which are factors that drive companies to adopt a certification approach, are related to anticipation and efficiency, which concern the reason for improving the company's image, internal processes, functional areas, maintaining the competitive position in time of economic crisis as well as the improvement of quality as part of the strategy of these companies [4].

Some organizations implement quality management systems based on ***external motives***, when aiming to enter new markets, meet product export requirements, or meet customer requirements. Organizations also implement quality management systems because of the desire to gain a competitive advantage or as a response to future customers' satisfaction. Additionally, organizations use certification in the marketing of the company in order to increase its customer portfolio [4].

Both Ruževičius [5] and Gotzamani [6] distinguish internal-motive (MI) and external-motive (ME) quality management system implementation, and internal-benefit (BI) and external-benefit (BE) quality management system implementation, as presented in Table 1 below.

Table 1. Internal and external quality management system implementation motives (developed by authors based on [1,3,5]).

Motives	Type	Benefits	Type
Decision of the highest authority	MI	Improved quality of products and/or services	BI
Improvement of quality of products and/or services	MI	Decreased number of incidents, rejections, and complaints	BI
Improvement of processes and procedures	MI	Increased productivity and/or efficiency	BI
Reduction in incidents, rejections, and complaints	MI	Decreased internal costs	BI
Used as a basis for reducing internal costs	MI	Improved profitability	BI
Improvement of communication in the organization	MI	Increased workforce motivation and retention	BI
Improvement of management–employee relations	MI	Employees have a better understanding of quality	BI
Used as a promotional and/or marketing tool	ME	Improved processes and procedures	BI
Maintaining and/or increasing the market share	ME	Elimination of excess work	BI
Demand and/or pressure of customers	ME	Better working environment	BI
Competitive advantage	ME	Better customer service	BI
Condition to compete in the sector	ME	Increased customer satisfaction	BE
Our competitors who have implemented ISO 9000 standards	ME	Expansion into international markets	BE
Direct way to a new market	ME	Greater competitive advantage	BE
To be a good example for suppliers	ME	Effective promotional and/or marketing tool	BE
Improvement of public image of the organization	ME	Improved quality of suppliers	BE
At the request of the Government	ME	Established and/or improved mutual cooperation with suppliers	BE
		Improved corporate image in the market	BE

The type of motivation for implementing quality management systems affects the performance of the system. Organizations that focus on real quality improvements and organizational needs achieve higher benefits from their QMS implementation in areas like quality and operational improvement, compared to those organizations that implement and seek certification of their QMS for external motives, for example, image or customer requirements. Thus, a QMS implemented based upon external requirements tends to focus more on compliance and control and less on organizational efficiency [7].

According to Gotzamani [6], another important part regarding the effectiveness of standards is related to their ability to actually improve quality (internal and external) and customer satisfaction. The question mainly arises due to the fact that the standards do not require any evidence of the overall success and benefits of quality assurance systems in certified companies. A company may well be certified according to ISO 9001 standard without having to prove the existence of operational, economical, or other customer-related benefits that it has achieved through its implementation [6], or certain organizations are involved in the implementation of the ISO 9001 standard for marketing purposes only, without actually aiming to improve their quality management [2].

At the same time, evidence suggests that quality management systems provide a critical and established structure with the potential to create value, contribute to product quality and operational performance, increase net asset value, and support continuous improvement [7].

Others claim that the major benefits of purchasing from ISO 9001-certified companies include better, assured, and consistent product and service quality with prompt and speedy supply (shorter delivery lead times); in this way, there are fewer complaints and a better image for the company. Improved response to customer complaints is seen as the most significant positive change in performance demonstrated by certified companies [8].

3. Materials and Methods

3.1. Research Aim and Methodology

The research aimed to determine which quality management standards are used in Lithuanian organizations that are operating in different fields of activity, as well as to reveal the motives for implementation and benefits of implemented standards and their practical application within the side of organizations.

The research was conducted between 23 January 2021 and 30 April 2021 (see the research sequence in Figure 1). Interviews were conducted with quality representatives from organizations operating in various fields of activity: manufacturers of food, electrical equipment and plastic products, service providers, cosmetics, and pharmaceutical companies.

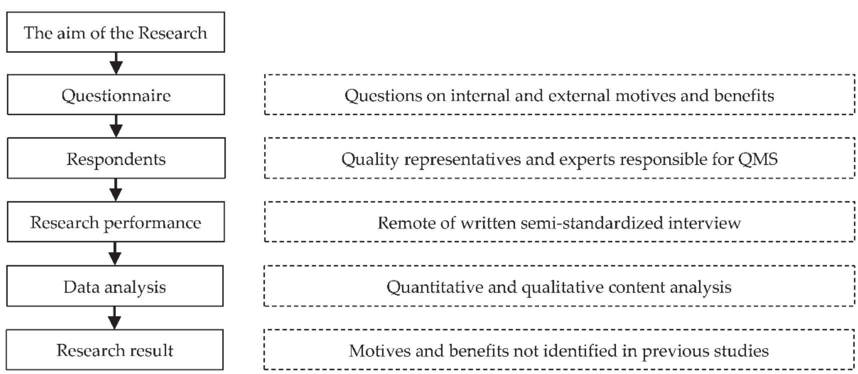

Figure 1. Research sequence.

Research limits—the research involved only organizations that are operating in Lithuania in different fields of activity and that have implemented quality management systems, with their quality representatives chosen to be the respondents.

Ten respondents were interviewed during the research (R1–R10) whose data were analyzed and summarized.

A questionnaire of the research was structured on the basis of internal motives (MI), external motives (ME), Table 1, internal benefits (BI), and external benefits (BE).

Respondents that participated in the research were quality representatives and experts who are responsible for quality management system implementation and assurance in their organizations.

The interview was conducted remotely due to the pandemic situation in Lithuania. All respondents received the questionnaire before the interview in order to prepare properly. Half of the respondents (R1, R4, R5, R7, R8) filled the questionnaire and provided answers in writing (OW). Remote interviews with other respondents were conducted via video communication platforms.

A quantitative as well as a thematic content analysis was applied to systematize the obtained qualitative research data.

3.2. Characteristics of Respondents

The research involved Lithuanian organizations with implemented quality management standards and operating in different fields of activity: manufacturing, trade, sales, services, customer service, and for-profit non-governmental organizations.

The respondents were quality representatives and experts who are directly responsible for the quality management system assurance in their organizations (Table 2).

Table 2. Qualitative research respondents from 1 to 10, their job positions, and data collection type.

Respondent Codes	Job Position	Data
Respondent (R1)	Process improvement manager	OW
Respondent (R2)	Quality director	OO
Respondent (R3)	Process development manager	OO
Respondent (R4)	Quality and food safety manager	OW
Respondent (R5)	Quality manager	OW
Respondent (R6)	*Non-disclosed*	OO
Respondent (R7)	Quality manager	OW
Respondent (R8)	Quality manager	OW
Respondent (R9)	Quality manager	OO
Respondent (R10)	Quality manager	OO
Note: OW—obtained in writing, OO—obtained orally		

3.3. Questionnaire Methodology for Semi-Standardized Interview Performance

A semi-standardized interview method was chosen for the research. The elements of the questionnaire were compiled by the authors on the basis of the generalized list of motives and benefits provided by Vyšniauskienė L. [3] and Ruzevicius J. [5]. Tables 3 and 4 provide a list of questions that were used for the research and evaluated, if motives and benefits from the list in Tables 3 and 4 existed in organizations, or not.

Table 3. Elements of the questionnaire compiled to evaluate QMS implementation motives.

Elements of the Questionnaire (Work Author)	Motives [3]	Type
4.a. What were the reasons for implementing the standard?	Decision of the highest authority	MI
4.b. External factors or internal demand?	Maintaining and/or increasing of the market share	ME
	Demand and/or pressure of customers	ME
	Condition to compete in the sector	ME
	Competitive advantage	ME
	Improvement of quality of products and/or services	MI
	Improvement of processes and procedures	MI
	Reduction in incidents, rejections, and complaints	MI
	Used as a basis for reducing internal costs	MI
	Improvement in communication in the organization	MI
	Improvement in management–employee relations	MI
	Used as a promotional and/or marketing tool	ME
	Competitive advantage	ME
	Our competitors who have implemented ISO 9000 standards	ME
	Direct way to a new market	ME
	To be a good example for suppliers	ME
	Improvement of public image of the organization	ME
	At the request of the Government	ME
Note: MI—internal motives, ME—external motives		

Table 4. Elements of the questionnaire compiled to evaluate existence of implemented QMS benefits in organizations.

Elements of the Questionnaire (Work Author)	Benefits [3]	Type
6.a. Habits and employee culture have changed	Employees have a better understanding of quality	BI
6.b. Has the investment paid off?		
7.a. Are the processes written?		
7.b. How widely are the processes communicated?		
7.c. Is there evident employee involvement?		
7.d. Employees are contributing to process improvement	Better working environment	BI
	Elimination of excess work	BI
8. How do you ensure compliance with processes?		
8.a. Are employees familiarized with the processes?		
10.a. How did the implemented standards affect the organization?	Improved processes and procedures	BI
	Increased productivity and/or efficiency	BI
10.b. Do you see the benefits of the implemented standards?		
11. How do you measure the level of the quality system?		
12.a. Has the quality of services improved?	Improved quality of products and/or services	BI
	Better customer service	BI
	Increased customer satisfaction	BE
	Improved quality of suppliers	BE

Table 4. *Cont.*

Elements of the Questionnaire (Work Author)	Benefits [3]	Type
12.b. Has the level of product defects decreased?	Decreased internal costs	BI
12.c. Has the number of non-compliances and complaints decreased?	Decreased number of incidents, rejections, and complaints	BI
12.d. Has employee motivation increased?	Increased workforce motivation and retention	BI
12.e. Has the company's profit increased?	Improved profitability	BI
12.f. Has the company become more attractive?	Improved corporate image in the market	BE
	Greater competitive advantage	BE
12.g. Has the circle of customers increased?	Expansion into international markets	BE
	Improved mutual cooperation with suppliers	BE
12.h. Is the public beginning to trust you more?	Effective promotional and/or marketing tool	BE
Note: BI—internal benefits, BE—external benefits		

The type of motives indicates if motives are internal (MI) or external (ME).

Elements of the questionnaire compiled to evaluate benefits of quality management standards existence are provided in Table 4.

Type of benefits indicates if benefits are internal (BI) or external (BE).

4. Results

An analysis of the research results proved that there are two main groups of QMS implementation motives—**external motives** (ME) and **internal motives** (MI).

The external implementation motives were particularly prevalent in the case of customer requirements.

Respondents stated that implementation of the standard allowed maintenance of one's position in the market, the gaining of a competitive advantage, and the ability to compete in the sector; however, only three respondents (R2, R4, and R6) stated that the emergence of the standard was the only reason why the organization decided to implement it. Six respondents (R1, R3, R5, R7, R8, and R9) stated that the emergence of the standard was determined not only by external motives but also by the desire of organizations to streamline and standardize their activities, improve their processes, and ensure process management, while one respondent (R10) pointed out that its only internal aim was to improve the quality of its services.

Data of the research were systematized and are provided in Tables 5 and 6 with such a methodology—if the answers were positive and it was suitable for all respondents, it was marked with a "+"symbol in Tables 5 and 6, but if respondents evaluated that the benefits of achieved topic were not related to implemented QMS, it was marked with a "/" symbol.

In summary, it can be stated that structure of motives for implementing quality management systems remain the same, and, in previous research, motives were internal and external. However, in terms of several organizations, it can be said that the external motive has become mandatory (R2, R5). The present research revealed that companies would simply not be able to operate without an implemented quality management standard (one of the approved GxP [9], ISO 17025 [10]). Refusal to implement such standards was not an option for them.

There were no observations during the research that would indicate that the motives for implementing standards may have stemmed from the initiative to reduce incidents, to use the standard for marketing purposes, or for the purpose of improving communication within the company between managers and employees, or of becoming a good example for suppliers. The aforesaid elements were revealed in the organization through the benefits of the QMS.

Table 5. Motives for implementing a quality management system in the organizations of respondents.

Motives	Type	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
Demand and/or pressure of customers	ME	+	+	+	+	+	+	+			
Competitive advantage (*supply selection procedures*)	ME	+				+			+		
Improvement of public image of the organization	ME				+					+	
Maintaining and/or increasing the market share	ME	+					+				
Condition to compete in the sector	ME		+			+					
Would not operate without relevant standard	ME		+			+					
Direct way to a new market	ME				+						
To use it as a promotional and/or marketing tool	ME										
Our competitors who have implemented ISO 9000 standards	ME										
To be a good example for suppliers	ME										
At the request of the Government	ME										
Improvement of quality of products and/or services	MI							+		+	+
Demand for standardized processes	MI			+					+	+	
Decision of the highest authority	MI					+					+
Improvement of processes and procedures	MI			+		+					
Increasing operational efficiency	MI	+				+					
Process management	MI			+							
Reduction of incidents, rejections, and complaints	MI										
Improvement of communication in the organization	MI										
Improvement of management-employee relations	MI										
Note: ME—external motives, MI—internal motives, [+]—positive answer, R1 <...> R10—respondent											

Even though not all organizations measured the effectiveness of QMS in the same way, all of them indicated the same thing regarding the benefits of quality management standards after their implementation.

The research results presented in Table 6 show that the external and internal benefits remain to be the prevailing ones. According to the respondents, ***internal benefits*** (BI) were an improved quality of products and/or services, a decreased number of incidents, improved profitability, increased workforce motivation (employee involvement), increased employee competence and procedural approach, improved processes and procedures (standardized procedures), easier management of organizations, and increased efficiency. ***External benefits*** (BE) were listed by respondents as increased customer satisfaction, expansion into new markets, competitive advantage, an improved image of the organization, and an increased circle of customers.

Benefits that were not revealed during the research were increased productivity and/or efficiency (BI), decreased internal costs (BI), elimination of excess work (BI), effective promotional and/or marketing tool (BE), improved quality of suppliers (BE), and improved mutual cooperation with suppliers (BE). Although these benefits have not been revealed, we cannot claim that they do not exist, do not occur, and/or have not been achieved in the organization. The study did not dive deep into the processes. For example, determining whether there was a decrease in excess work would require a thorough investigation by accessing the organization's internal processes, checking each stage of the process, the cycle time, the operation of the process, and its effectiveness.

Table 6. Quality management system benefits in the organizations of respondents.

Benefits	Type	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
Improved processes and procedures *(standardized procedures)*	BI	+	+		+		+	+	+	/	+
Employees have better understanding/competence of quality	BI	+		+	+	+	+		+	+	
Improved quality of products and/or services	BI	+	/	+		+		+	+	/	+
Decreased number of incidents, defects, and complaints	BI	+	/	+	+	+				+	+
Improved profitability	BI	+	/	+	+		+	+	/	+	/
Increased workforce motivation and retention (*involvement*)	BI	/	+	+	+	+	/	/	/	+	
Easier management of the company	BI		+							+	
Increased efficiency	BI	+			+						
Better working environment (*working conditions*)	BI	+									
Better customer service	BI										+
Increased productivity and/or efficiency	BI										
Decreased internal costs	BI										
Elimination of excess work	BI										
Greater competitive advantage	BE	+		+	+		+	+		+	
Increased circle of customers	BE	+		+	+		+	+	/	+	
Expansion into international markets	BE	+		+	+	+	+				
Improved image in the market and became more attractive	BE			+			+	+	+	+	/
Increased customer satisfaction	BE	+						+			+
Effective promotional and/or marketing tool	BE										
Improved quality of suppliers	BE										
Improved mutual cooperation with suppliers	BE										

Note: BI—internal benefits, BE—external benefits, [+]—positive answer, [/]—benefits of achieved topic are not related to implemented QMS, R1 <...> R10—respondent

A significantly improved quality of products/services and a decrease in the number of incidents and defects/complaints was observed in the organizations. Six out of ten of the organizations indicated that the quality of their services has improved since the introduction of QMS, and there were two organizations (R2, R9) that pointed out that this improvement was not solely related to the implementation of the standard or was only related partially. Six out of ten of the organizations indicated a reduced number of incidents, defects, and complaints within the company, and one respondent indicated that this was unrelated to the implementation of QMS.

Six out of ten of the organizations also talked about improved profitability and increased workforce motivation (employee involvement), increased employee understanding of quality, and improved processes and procedures (standardized procedures) by indicating that their company's profit increased after the implementation of the standard. However, these data were provided by respondents based on their intuition and not on actual facts, and 3/10 of the organizations (R2, R8, and R10) did not think that the growth of their company was linked to the implementation of QMS. Five out of ten of the respondents indicated an increase in employee motivation and involvement in the improvement of the organization's internal systems. Four out of ten of the organizations indicated that mostly there was partial involvement, which occurs only when employees see benefits (R8) or a lack of involvement due to employee turnover among lower-level employees.

As many as 7/10 of the organizations claimed that their organization had become more mature with better awareness of why it is important to have an implemented quality system, which indicates that a culture had developed within the organization. Seven out of ten of the organizations revealed that after the implementation of the standard(s), clear standardized processes and responsibilities emerged, which greatly facilitated the management of the organization's activities. One organization (R9) did not link process improvement to the implementation of a standard alone, since a food safety system was already in place, and the aim was to improve it.

Only 3/10 indicated an increase in customer satisfaction (BE) after QMS; however, these results are not sufficient to declare that customers of the remaining organizations are dissatisfied, since organizations do not conduct surveys, or the respondent did not indicate this during the survey. Five out of ten of the respondents indicated that opportunities to enter new markets emerged, and 6/10 of the organizations indicated an improved competitive advantage. An improved image of the organizations in the market (5/10) was observed, while two organizations (R2 and R9) stated that management in their company has become easier and efficiency has increased (R1, R4), and even 6/10 of the organizations reported an increased circle of customers.

After evaluating the research results, it can be seen that organizations implementing quality management systems based on both external and internal motives benefit in the end from the implemented quality management standard:

1. If the QMS implementation motive of an organization was customer or market requirements, the organization was able to enter new markets as the end result;
2. If the QMS implementation motive of the organization was internal: to improve the company's operations, its management and operational efficiency, the management of the company became easier in the end, with the formation of employee culture, awareness, and procedural thinking, which helps improve the organization and encourages it to move forward.

5. Discussion

According to Ruževičius [11], apart from "traditional" quality (ISO 9001 [12]) and environment (ISO 14001 [13]) management systems, Lithuanian companies uses systems—ISO 22000 [14] (food industry chain quality management), ISO/IEC 20000 [15] (IT service management system), good manufacturing practice (GMP) [16], Forest Stewardship Council (FSC) [17]; forest management and wood processors certification, ISO/IEC 17021:2006 [18] (requirements for bodies providing audit and certification of management systems), ISO 13485 [19] (for medical devices), SA 8000 [20] (*Social accountability*), ISO/TS 16949 [21], ISO/IEC 27001 [22], CMMI [23], BRC Global Standard [24], etc.

The survey revealed that the core implemented standards were ISO 9001 [12], ISO 14001 [13], and ISO 45001 [25], while the rest of the standards were specialized according to the business area, i.e., implemented based on the organization's activities: a plastic packaging manufacturer implemented BRC [24], while an electricity company implemented ISO 27001 [22] and ISO 17025 [10]. A company providing clinical research services to pharmaceutical and biotechnology companies and manufacturers of medical devices implemented ISO 13485 [19] and ISO 22716 [26], and food and egg producers implemented BRC Foods [24], IFS Food [27], ISO 22000 [14], and HALAL [28] systems (see Table 7). It can be seen that the trends in the implementation of standards remain similar; however, new systems were also introduced—ISO 22716 [26], ISO 45001 [25], IFS Foods [27], and HALAL [28].

Vyšniauskienė L. [3] found that organizations have 7 internal (MI) and 10 external (ME) motives, as well as 11 internal (BI) and 7 (seven) external (BE) benefits.

Four motives that were not identified in previous research were found during this research: (1) organizations would not operate without a standard (ME), (2) improvement of operational efficiency (MI), (3) procedural management (MI), and (4) increased demand for standardized processes (MI). Current research revealed 3 benefits: (1) easier management of the company (BI), (2) increased efficiency (BI), and (3) increased circle of customers (BE).

Table 7. Implemented standards in organizations.

R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
ISO 9001 ISO 14001 BRC	ISO 9001 ISO 13485	ISO 9001 ISO 14001 ISO 45001	BRC Food IFS Food ISO 14001 RSPO	ISO 9001 ISO 14001 ISO 45001 ISO 27001 ISO 17025	BRC Food HALAL ECO	ISO 22000 ISO 13485 ISO 22716	ISO 9001 ISO 14001 ISO 45001	BRC Food	ISO 9001

Note: R1 <...> R10—respondent

It is likely that the research did not reveal all the benefits of implementing the standard. It can be concluded that increased productivity, reduced internal costs, and elimination of excess work are the main benefits of an organization included in the empirical research; however, this was not revealed. The main reason for this is the scope of the research, since, in order to determine productivity, costs, and elimination of excess work, the research should take place continuously within the organization itself, with the possibility to access its processes.

The Concept of the Model of Benefits of Standards

When implementing a quality management system, organizations can choose one motive or another depending on their objectives set for the quality management system—whether the motive is only external or internal or both external and internal.

The benefits of a standard can be determined when the system is not yet fully implemented. This is reflected when employees contribute to the improvement of the organization's quality system and development of its processes. This should be particularly evident when an organization implements QMS for internal rather than external motives. In addition to employee involvement, the benefits of improving processes and procedures is also revealed later on, with the appearance of clear responsibilities and easier management of an organization at the process level. This benefit can be revealed regardless of the implementation motives (either external or internal), since the standard itself obliges standardization of the system.

Summarized results of this research (see Tables 5 and 6) provided the basis for proposing the model of systematized motives and benefits of quality management standards (see Figure 2).

The benefits of quality management standards that directly contribute to the growth of the organization (improved quality of products/services, reduced number of incidents, increased circle of customers and profit of the company, etc.) were also revealed.

The research proved that not only that the same motives and benefits for implementing QMS in organizations remain, which were revealed by previous studies, but that there are other *external motives*, which would not operate without the relevant standard (ME), and *internal motives*, increasing operational efficiency (MI), process management (MI), and demand for standardized processes (MI). Additionally, other benefits, such as *external benefits*—increased circle of customers (BE)—and *internal benefits*—easier management of the company (BI) and increased efficiency (BI)—were revealed.

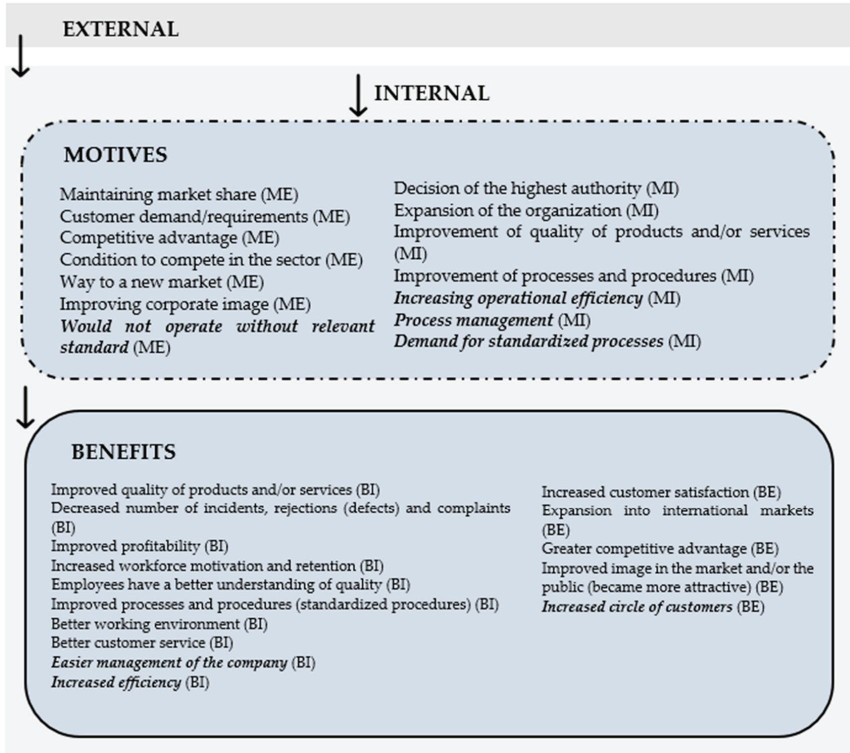

Figure 2. Model of systematized motives and benefits of quality management standards.

Organizations should monitor and evaluate whether the implemented QMS system provides the added benefits that were expected before implementation, regardless of whether the motives were internal or external:

1. If the motive of an organization to implement QMS was only external, the organization should set at least the following system monitoring indicators for the end result:
    a. Improved profitability;
    b. Increased circle of customers;
    c. Increased customer satisfaction.
2. If the motive of an organization to implement QMS was internal (improvement of the company's activities and its management and operational efficiency), it should set indicators allowing the organization to determine the involvement of its employees and operational efficiency. Various qualitative indicators could be determined, such as:
    a. Process quality level indicator;
    b. Complaint and defect reduction indicator;
    c. Proposal system for process improvement;
    d. Customer surveys, etc.

If an organization has implemented quality management standards for external reasons, and if it achieves its set result (increased circle of customers, expanded market share, increased profit of company), it should consider changing its motives to internal ones, and aim to not only meet customer demand/requirements but also to improve the company's internal system and employee involvement.

Organizations should establish clear key performance indicators' (KPI) process monitoring and evaluate their system to see if the implemented quality management system provides the added value that they expected before the QMS implementation, and accreditation companies should take this more into account in certification or annual follow-up audits and make sure that the organization monitors these indicators.

6. Conclusions

1. Organizations implementing quality management systems based on both external and internal motives benefit from the implemented standards at the end. If the motive for the implementation of an organization's QMS is customer or market requirements, such an organization is able to enter new markets in the end. If the motive is internal (improvement of the company's activities and its management and operational efficiency), the management of the company becomes easier in the end with improvements in employee culture, awareness, and procedural thinking, which help further develop the organization.
2. The data of the empirical research indicate that, after the implementation of QMS, the level of quality improved, the number of incidents and defects (complaints) decreased, and employee involvement and understanding of quality increased. More than half of the respondents indicated an increase in their company's profits, increased customer satisfaction, easier management of the company, and increased efficiency; however, results such as data on the company's profits were provided by respondents based on their intuition instead of actual facts. A conclusion can be drawn that organizations see the implemented quality management standards as beneficial; however, these data are not based solely on the internal indicators of companies.
3. The authors suggest such a possible standardization and quality management development insights for future research: (a) the evaluation of real and comparable values of management systems' certificates, delivered by different conformity assessment institutions; (b) the evaluation of the efficiency and influence of standardization, QMSs, environmental management systems, and eco-labelling tools on a company's added value and a country's gross domestic product.
4. The interviews were conducted with quality representatives/ experts but not with operational level employees, and the research was conducted with a small amount of organizations based in Lithuania. Future research should be performed with organizations in foreign countries and interviewed with operational-level employees.

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standards

Article

Two Obstacle Factors for Technological Standardization: The Viewpoint of Technological Frame

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Abstract: The concept of the Internet of Things (IoT), which is an architecture in which devices supplied by various firms and services operated by distributed organizations exchange data, has been adopted in an increasing number of situations. While there are cases in which a small number of limited organizations collaborate on certain ecosystems based on proprietary specifications, the development of open standards is increasingly important for building scalable ecosystems because of the introduction of the concepts of Industry 4.0 and Society 5.0. Under these circumstances, there are two types of barriers to standardization. One barrier is the lack of shared frames for architectural design. The other barrier is the lack of awareness of the need for scalability. In this paper, we analyze the factors underlying these two barriers and discuss the path towards breakthroughs.

Keywords: collective technological frame; craftspersonship; ecosystem; platform; innovation; Internet of Things; smart city; connected industry; Industry 4.0; Society 5.0

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1. New Modes of Innovation and Standardization Research

New modes of innovation that began to appear in the 2010s, such as smart cities and autonomous vehicles, function only when provided with mashed up data generated by diverse sensor devices via the Internet and the functioning of those modes varies based on processing results. This situation can only be attained when various firms and services operated by distributed organizations exchange data in real time by adopting the concept of the Internet of Things (IoT). The concept of implementing new services with the real-time processing of big data by an autonomously developed algorithm through artificial intelligence (AI) has been named Industry 4.0 and Society 5.0, i.e., concepts which are promoted by governments and companies worldwide. Four design principles have been identified as integral to Industry 4.0, namely, interconnection, information transparency, technical assistance, and decentralized decisions [1], and this concept has encouraged data distribution and sharing among distributed manufacturers.

The Connected Industry that is designed as part of Society 5.0, which aims to innovate society as a whole [2], aims to leverage IoT technology in a wider range of five priority areas: "manufacturing and robotics", "plant/infrastructure safety management", "automated driving and mobility services", "biotechnologies and materials", and "smart life" [3]. The Japanese Industrial Standards Committee (JISC) has proposed a specification based on Society 5.0 titled "Gap analysis for standardization of sustainable and human-centred societies enabled with cyber physical systems" for an International Workshop Agreement (IWA 39) [4]. This focus on a "human-centred" society is one of the core values of Society 5.0.

Many firms, such as Amazon [5,6], have opened application programming interfaces (APIs) for their own business models [7], which constitute the API economy [8]. The API economy consists of data with different specifications for each data provider. Few data providers focus on interoperability among data from different firms. Therefore, data aggregators, brokers, and service providers have emerged to allow for the utilization of data from different sources [9,10]. There have been many information silos, which have been barriers to the realization of Industry 4.0 and Society 5.0.

On the other hand, to develop services utilizing various sources of data on the city OSs used for smart cities, interoperability among such data is required. The development of open standards is increasingly important for building scalable innovation ecosystems [11]. Even if the number of devices connected to the Internet increases, big data that can be analyzed will not be produced unless the data generated by devices are integrated. Building an ecosystem where compatible data are generated, shared, and utilized by each device is necessary to create sustainable services. There have already been several attempts made by governments to achieve mutual accessibility of data, such as Germany's Industrial Data Spaces and the Government of Japan's Society 5.0 smart reference architecture. Private consortia such as the Industrial Internet Consortium (IIC) and standards bodies such as the IEEE [12] are also engaged in the process of formulating standard technical specifications related to the IoT. However, data exchange ecosystems and smart cities based on standard technical specifications remain in the proof-of-concept stage.

To realize compatibility among distributed data resources, there must be a common syntax and vocabulary as well as other specifications. However, different industries and regions may use the same concept but employ different terminology. Even given the same temperature data, the accuracy required differs greatly between machine part manufacturing lines and medical examinations. Operational differences among diverse stakeholders are a major impediment to standardization based on the concept of IoT. In an era when an unspecified number of devices are not interconnected via the Internet, it is sufficient if mutual availability among devices is realized within a specific company or within the same industry, a situation which would be sufficient for each specific industry or use case. Standardization has been implemented. When only a few devices were interconnected, it was sufficient for most services to function without interoperability among distributed and diversified devices. Therefore, most compatibility standards are set within industries and for specific use cases. Working groups in many organizations devoted to standard development have developed standards for specific industries and domains. However, the same data, such as footprints, are utilized for multiple unrelated applications, such as mobility services and energy management, in the coordination of the city OSs used for smart cities. Companies and organizations that design hardware and services for a variety of purposes must overcome contextual differences to achieve mutual availability in the era of the IoT.

Moreover, these standards tend to prevent innovation [13] because they function by reducing the variety of goods [14]. Moreover, excess inertia locks standardized specifications into previously widespread specifications [15]. Interoperability encourages data integration among diversified sources. At the same time, standards prevent data owners from changing their original or industry-specific specifications. Standards make existing businesses, which have been designed according to industry-specific rules, more efficient. However, they also interfere with the innovation through new cross-industry data transactions.

While these theories emerge primarily from the field of economics, a socio-technical system approach is also needed to discuss standardizations related to the IoT and smart cities that affect all areas of life. The socio-technical system approach shows the relation between technical and social systems and demonstrates that their interplay is essential for technology development success [16].

There are two types of barriers to standardization in building ecosystems with massive data exchanges in the IoT era. One barrier is the lack of shared frames for architectural design. The other barrier is the lack of awareness of the need for scalability. In this paper, we analyze the factors underlying these two barriers and discuss the path towards breakthroughs.

2. The Lack of Shared Frames for Architectural Design

2.1. City OS and Standards as a Platform

Many services developed in the IoT era, such as smart cities and mobile services, are provided on platforms such as smartphone OSs and city OSs. In short, the design of services is a complementary good for ecosystem platforms. An OS is designed as a core component in systems, and an API, the interface design with other components, defines the functions of the entire system. The concept of Next Generation Service Interfaces (NGSI) is one of the core technical specifications of Fiware (Fiware official website: https://www.fiware.org/developers/ accessed on 8 August 2021), which is a city OS popular in Europe. The NGSI-LD, an updated NGSI data model incorporating the concept of linked data, has been standardized by the European Telecommunications Standardization Institute (ETSI) (GS CIM 009-V1.1.1-Context Information Management (CIM); NGSI-LD API https://www.etsi.org/deliver/etsi_gs/CIM/001_099/009/01.01.01_60/gs_CIM009v010101p.pdf accessed on 8 August 2021). Therefore, API specification standards influence the functionality and competitiveness of the entire ecosystem.

Not all standards play a role of platform [17]. However, NGSI-LD in Fiware is a typical case of a standard used as a platform. Such specification functions as a set of standards for providing commonly required functions [18,19]. The APIs of Fiware are public standard specifications developed by the European Commission, and at the same time, Fiware itself is an open-source software developed by a variety of organizations and individuals. Members of the Fiware Foundation include public institutions, private companies, and private individuals. Forms of cooperation between platformers and partners are determined by the specifications of the API. The API and other resources are provided to partners and referred to as boundary resources [20].

Development of Fiware is conducted on GitHub, which is a popular web service for collaborative software development. Therefore, it is easy to participate in development activities and to propose functions and codes to be added. Even if the required functions are agreed upon among participants, it is not easy to reach consensus in the process of developing implementation methods and specification details. Technology development is defined as the process, tasks, and decisions that firms embrace to select and integrate a new or existing technology into a final product or service [21,22]. Smart cities are a form of digital transformation in community management. Digital transformation refers to a revolution in how things, including products and services, operate and how people interact with one another [5,23]. Moreover, applications applied to technologies will be newly discovered as they become more widespread [24]. The diversity of participants and the ease of making proposals lead to increased coordination costs because the overall picture of smart cities and the functions to be developed by each participant may be diverse.

In an ecosystem with various stakeholders involved in operation, compatibility of the data processed by each application is essential for various applications to work together on city OSs. Therefore, it is necessary for the API specifications of city OSs to be uniformly compliant among stakeholders as a standard. Moreover, any standards are developed by agreement among stakeholders. Agreement can be achieved only with a common technological frame. Upgrading may involve changes in the concept and role of specification. To realize changes in standard specifications, a shared technological frame [25,26] among stakeholders is necessary. The upgrade of Hyper Text Markup Language (HTML) at the World Wide Web Consortium (W3C) is a typical example of a framing contest in standardization.

2.2. HTML Update as a Framing Contest

The ideal role and function of the core module depends on the interests of the stakeholders that comprise ecosystems. If an ecosystem is not dictated by a particular organization, keystone [27], or platform leader [28], there may be competitions concerning who takes the initiative for the design of the platform when trying to revamp the ecosystem by upgrading an open platform. In other words, upgrading standards for designing platforms sometimes become races among technological frames [25,26].

The concept of frame was originally used in social movement theory. To gain support, activists try to establish a collective frame [29] by making their own frames widely accepted. The scope indicated by "society" is not limited to one region or country. In other words, conflicts among frames are not limited to a single region and may develop into an international agenda, such as environmental issues [30] and international trade [31]. Therefore, the concept of frame has been applied by management scholars to analyze drastic changes in market structure (such as [32–34]).

From the viewpoint of innovation and the evaluation of emerging technologies, in short, technological frame [25] or technology frame [26] has come to be an important factor for building business models, and cases such as cochlear implants [35], DTP and digitization of newspapers [36], and digital photography [37] have been analyzed.

The technological frame used may limit prospective applications of emerging technologies within organizations [25]. Bijker and Pinch [38] pointed out that any technological artifact is recognized differently in terms of its significance for each organization and interacts with each organization based on different contexts. Therefore, each organization establishes a different frame for any technological artifact. Such diversity causes differences among strategies for utilizing technologies [25]. Acha [26] pointed out that pass dependency causes such differences.

There may be more than two different frames for new technologies, such as when threats and opportunities are both present within the same organization. This coexistence is a framing contest [34].

2.3. Competition and Cooperation for Standard Setting

Not all standards play a role in platforms, but some do [17]. HTML, which used to be merely a mark-up language for stable documents, has transformed into a runtime environment for web applications. HTML5, one of the specifications proposed as a successor to HTML 4.01, can be regarded as a platform because it provides functions, such as certain APIs, commonly required for the operation of various web applications and realizes coordination among these functions [18,19]. HTML5, which is the newest version of W3C's standard, realizes "web applications", such as Google Spreadsheet instead of Microsoft Excel, thereby allowing applications such as spreadsheets to run on servers instead of on client hardware regardless of the type of browser used by the client. Multiple users editing one specific web application is a typical case of innovation through standardization. Web applications allow multiple users to edit a single file simultaneously. In addition, since the files are on the cloud, the user can work smoothly using multiple terminals regardless of whether he or she is at home, at work, or away. The innovation of web applications meets the demand caused by the COVID-19 epidemic for updates to operations, especially concerning collaborative practices.

A platform is a component commonly utilized by multiple complements [19,28]. The HTML5 predecessor specification, XHTML Module: Extensions to Form Controls, was first proposed in 2003. The following year, in 2004, the original concept of HTML5 was proposed by two browser vendors, Mozilla Foundation and Opera Software, but was officially rejected because there was a different upgrade plan.

W3C staff members, including Tim Berners-Lee, who serves as Director, and several member companies share the different technological frame of advanced HTML developed with eXtensive Markup Language (XML). It was Tim Berners-Lee's plan to use this technology to enhance the functionality of websites with XML technology. XML was widespread as a data format for machine processing at the time. The difference between the existing HTML and XHTML depends on whether or not the data consist of XML-based syntax. Therefore, the documents sent from servers in response to requests never change dynamically. Changes displayed to users on browsers occur only with new requests and the download of new documents (Figure 1). The technological frame of XHTML is to preserve the role of websites as stable documents, similar to existing HTML. On the other hand, HTML5 is designed as a runtime for web applications. HTML5 documents change dynamically without reloading through data transactions via application programming interfaces, such as documents used by native applications such as Microsoft Word (Figure 2).

HTML5 was supported by web content creators who did not need the new features of XHTML realized by XML technologies. XHTML was supported by companies providing solutions for enterprises (such as IBM) and researchers of markup languages, such as W3C staff like Tim Berners-Lee. At the beginning of the 21st century, two different technological frames for the web platform coexisted, and a collective technological frame had not yet been formed. In short, there was a typical framing contest at W3C.

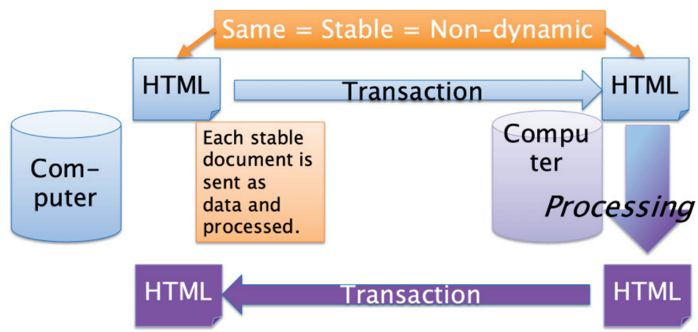

Figure 1. Concept of early HTML.

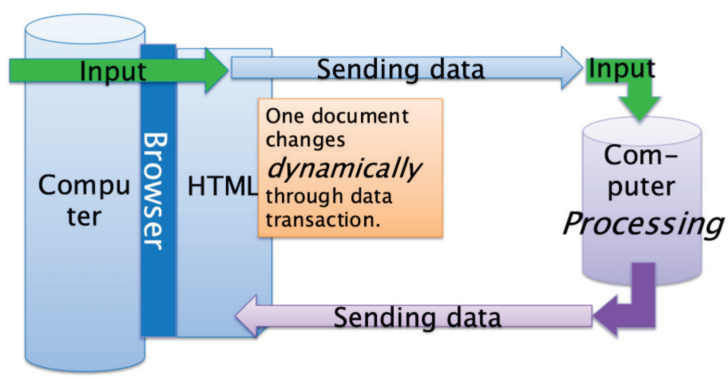

Figure 2. Concept of HTML5.

The result of this framing contest was the victory of HTML5, which was achieved by successfully gaining the support of members of the standards body and website developers and by implementing the implementation of HTML5 in Apple and Google products. HTML5 was welcomed by organizations and individual engineers both inside and outside the standards body. Moreover, Apple and Google joined the original proponents of HTML5, Mozilla Foundation and Opera Software, as advocates and actively promoted HTML5 to website developers. The concept of HTML5 has become a collective technological frame of the web platform ecosystem [39].

Ecosystem designs based on concepts such as IoT and smart cities tend to be enormous and involve diverse stakeholders. Sometimes, conflicting stakeholders must coexist within the ecosystem. In other words, it is difficult to avoid the coexistence and competition of multiple technology frames. Orlikowski and Gash pointed out that technological frames tend differ between engineers and end-users [25]. Engineers tend to focus on the technologies themselves rather than their use in specific contexts. On the other hand, users sometimes misunderstand and become confused by technologies. From the perspective of multisided market theory [40–42], it is important to form a collective technological frame among the diverse stakeholders that make up the ecosystem, such as engineers, end users, and residents. The question of how to form a collective technological frame among diverse and conflicting stakeholders has emerged as an important topic in standardization research.

3. Trade-Offs between Scalability and Diversity

3.1. Standardization in the Industrial Internet and Social Change

The concept of the Industrial Internet, in which all physical devices are connected to the Internet and operated by control based on data processing, has long been advocated. Studies on the digitalization of human operation in manufacturing have been conducted (e.g., [43].) The Industrial Internet Consortium (IIC) was founded in 2014 by AT&T, Cisco, General Electric, IBM, and Intel. Google and other Silicon Valley companies are also developing many IoT-related technologies, products, and services.

In 2006, before the IIC, a cross-sectoral consortium was established; i.e., the Continua Health Alliance (CHA) was launched to develop a personal telehealth ecosystem [44]. The purpose of the CHA was to develop interoperability guidelines [45], and members of the organizations have contributed to standardization activities in multiple standard development organizations. The CHA has developed a complex e-health information communication ecosystem that consists of a specialized medical profile for ISO/IEEE 11073 interoperability, such as USB, Bluetooth, and ZigBee [46]. CHA activities are deployed in the limited field of healthcare, especially for long-term follow-up monitoring outside of medical institutions for patients with lifestyle-related diseases, and it is a successful example of a private sector project to establish a sustainable framework with a de-jure standard.

On the other hand, as mentioned at the beginning of this article, there are government-led initiatives for sharing data not only among single applications but also among all types of devices, including manufacturing facilities, to achieve a digital transformation of the entire social economy, such as Industry 4.0 in Germany and Connected Industry in Japan. The German Industry 4.0 (Industrie 4.0) strategy was announced by the German government in 2011, and European activities for promoting the Industrial Internet have become widespread. Based on the concept of Society 5.0, Germany subsequently organized Platform Industrie 4.0 in 2013 and published Reference Architecture Model Industrie 4.0 (RAMI 4.0) (Platform Industrie 4.0 Reference Architectural Model Industrie 4.0 (RAMI4.0)—An Introduction. Retrieved from https://www.plattform-i40.de/PI40/Redaktion/EN/Downloads/Publikation/rami40-an-introduction.pdf?__blob=publicationFile&v=7 accessed on 9 August 2021) in 2015 to improve the environment for the realization of Industrie 4.0.

The Japanese national government began to promote Connected Industry in 2017 (Ministry of Economy, Trade and Industry of Japan. (2017). "Connected Industries" Tokyo Initiative 2017. Retrieved from https://www.meti.go.jp/english/press/2017/pdf/1002_004b.pdf accessed on 9 August 2021). After that, the Japanese government advocated Society 5.0, which promotes data utilization not only in the industrial field but also in society as a whole [2] and released Society 5.0 Reference Architecture. Japan's Ministry of Economy, Trade, and Industry has launched gBizID, a set of digital identification services (Ministry of Economy, Trade, and Industry of Japan. (2020). Provision of gBizIDs to Systems for Administrative Procedures in Local Governments and Other Organizations to Start. Retrieved from https://www.meti.go.jp/english/press/2020/0805_002.html accessed on 11 August 2021), and developed Infrastructure for Multilayer Interoperability (IMI), a common vocabulary framework for data transaction among public and private sectors (Ministry of Economy, Trade and Industry of Japan. (n.d.). What is IMI. Retrieved from https://imi.go.jp/goi/imi-about-en/ accessed on 11 August 2021) based on the Basic Act on the Advancement of Public and Private Sector Data Utilization (Basic Act on the Advancement of Public and Private Sector Data Utilization retrived from the System of Japanese Law Transration of Ministry of Justice, Japan; http://www.japaneselawtranslation.go.jp/law/detail/?printID=&id=2975&re=01&vm=02 accessed on 11 August 2021).

Despite the existence of technical specifications prepared by the government and many experimental demonstrations of smart factories and smart cities, social implementation of standardization has not progressed well. While the activities of a private consortium led by a giant platform with significant market influence, such as Google or Intel, play a central role in creating implementation cases in the United States, much expense and time are needed to reach consensus and develop standards for the transformation of society and industrial structure with information technologies in Germany and Japan. The increase in and diversification of participants causes delays in the standardization process [47–49]. However, there are areas where the diversity of stakeholders is not the only barrier. The process of manufacturing, especially craftsmanship, is ongoing and has not been digitized.

In Japan, where the birth rate is declining and the population is aging, it is becoming difficult to hire and develop human resources that can personally inherit the tacit knowledge and skills used by craftsmen. In 2000, a round-table conference on manufacturing was established, which discussed the need for policies to promote technology succession. In Japan, the private sector has also established the Industrial Value Chain Initiative (IVI), which aims at social implementation of data distribution and control technology in manufacturing and distribution processes (What is IVI?—Industrial Valuechain Initiative https://iv-i.org/wp/en/about-us/whatsivi/ accessed on 11 August 2021). Both the public and private sectors have invested in the digitization of craftspersonship, interconnection among machinery, and reference architecture. They have also developed technological infrastructure and legal systems for data exchange. Nevertheless, the electronic accumulation and utilization of knowledge in the manufacturing industry has not progressed well. I maintain that there are hidden issues of standardization research involved in this case.

3.2. Craftspersonship, Innovation, and Standardization

There are several types of technologies that are targeted in the implementation of the Industrial Internet, i.e., electronic controls in manufacturing that are based on data collected and exchanged through the Internet. MacKenzie and Wajcman classified technology into three layers: (1) “physical objects or artifacts”, (2) “activities or processes” and (3) “what people know as well as what they do” [50].

The digitization of the procedure, which originally involved manually collecting measurement data and operating based on numerical values, runs smoothly [51]. Digitization is relatively acceptable in areas where there is a strong need for automation, such as household appliances. Panasonic launched an electronically controlled coffee roaster, “Panasonic the Roast, AE-NR01”, in 2017 in Japan. The roaster can download roasting profiles from the famous roaster, Naoki Goto. This process allows the consumers to enjoy the same roast as a famous roaster at home.

Panasonic released a smartphone application that allows users to create their own roasting profile in 2018. The machine and the application are used by multiple coffee shops and roasting companies. In the interview, three famous coffee shops and roasting companies used the machine for sample roasting in new product development. However, the use of electronic roasting profiles is limited to sample roasting (Interview with Tokado Coffee, Golpie Coffee, and Rec Coffee in PR article of Panasonic in Japanese. Retrieved from https://akatiti.net/articles/view/416 accessed on 11 August 2021). The amount of beans that can be roasted at one time with AE-NR01 is 50 g, which is too small to produce products for sale.

The batch of a commercial coffee roasting machine is at least a few kilograms. Figure 3 shows a small commercial roaster from a Japanese start-up roastery with a batch of 4 kg. All preinstalled instruments are analogue. The digital timer, without Bluetooth and other communication modules, was attached after installation by the roastery. The roaster creates his original roasting profile by entering the temperature changes into an Excel spreadsheet each time (Figure 4). The batch of roasting for large-capacity models with an automatic control function and a temperature sensor is 10–70 kg. However, the function of importing electronic roasting profiles is not implemented in such a commercial roasting machine with sensor control function.

Figure 3. Small commercial roaster with a capacity of 4 kg.

Figure 4. A roaster adjusting the heating power based on the analogue thermometer.

The procedure for product development is determined as follows: a sample profile is created on a small capacity machine based on home use, and then the product is produced on a large capacity commercial machine. Therefore, it seems reasonable for the electronic profile information created by Panasonic's software to be imported directly to the commercial machine and then corrected to fit large commercial roasters. However, as of August 2021, it is not yet possible to exchange profiles between machines from Panasonic and those of other commercial vendors, such as Loring.

Coffee is an aromatic delicacy and scientific studies on coffee itself and additives such as milk [52–54] have been conducted. The extraction process is important [55]. However, roasting is also the most important factor affecting the aroma when drinking [56]. Therefore, the effect of roasting on aroma has also been analyzed [57–64]. Studies on sensing technology for roasting conditions are also being conducted [65].

Advances in preservation technology have made it possible to distribute roasted beans while preserving their aroma [66]. In other words, roasting is one of the most important factors in determining the market value of coffee, which is why many craftsmen have devised and refined roasting techniques. Utilizing these research results, high-precision control of coffee roasting is possible, and US manufacturers such as Loring have implemented such functions. However, profile data cannot be shared among devices, even those from the same manufacturers. It is natural to speculate that the barrier to data exchange is not technological.

One possible explanation for this fact is the diversity of cognitive frames discussed earlier in this paper. Sensory studies performed by cupping experts often use different expressions for the same condition in scientific measurements [67]. In addition, the vocabulary for taste expression is constantly being updated [67,68]. In other words, there is widespread belief within and outside the industry that sensing chemical component quantities and ratios alone is not sufficient to describe roasting techniques. From an engineering and scientific point of view, the difference in expression can be overcome by quantification of the measured component amounts.

Coffee is a luxury item and users have diverse tastes. In addition, products are often not selected based on clarified and quantified criteria. Coffee roasting techniques are perceived differently than those used in automated mass production processes. It is necessary to further understand the roasting technology itself.

Coffee, which has a variety of products linked to the personality of individual craftspersons, has a variety of taste and aroma evaluation vectors that compose the value provided. Some categories of technologies concern the integration of process and knowledge. Some of these kinds of technologies are sticky to the individual craftsperson. Sticky information is an important factor in innovation [69,70]. If stickiness is the key to competitiveness, then it is natural for craftspersons to hesitate to contribute to the digitalization of their skills and the standardization of shared data.

Coffee is not the only product category with these characteristics. Most foods have a particularly strong tendency towards such idiosyncrasy. In the cereal food market, the manual manufacturing method is becoming more popular, as artisan bread has become popular [71]. DeVore pointed out that technological development is influenced by norms and values in society [72]. Craftspersons have avoided pursuing scalability and standardizing technology in markets where brands that supply small quantities of highly unique and high-quality products are popular. Skolimowski pointed out that technology is a form of human knowledge [73]. If technical knowledge remains disparate and unsystematized, it is extremely difficult to integrate and standardize it, even if it is digitized. However, the concept of the IoT applies to all devices that operate in a standalone manner. Therefore, all technologies are subject to digitization and standardization. The diversity of procedures, classification, and vocabulary is not the only barrier to standardization in such industries.

Analysis of the case of coffee roasting profiles raises research questions whether the technology is evaluated to be standardized or not, and, if not, questions of how to foster such recognition are arising.

4. Conclusions

A reduction in communication and information processing costs has led to ubiquitous sensors, creation of big data, generalization of artificial intelligence utilization, and real-time control of various kinds of systems. With these changes, all socio-economic activities are being updated by innovation through standardization in technology.

In an ecosystem composed of cyber-physical systems, all components are required to work together through shared data. Due to such changes in the situation, the following two research issues have emerged in the field of standardization. The first issue is how to foster a collective technological frame for core platforms. The other issue is how to establish scalability through standardization in areas where competitiveness as differentiation is pursued as craftspersonship. The former issue requires careful analysis of the process of consensus building among stakeholders with conflicting interests for the former, while the latter requires shifting the common perception of business models across a certain industry. Standardization research in the IoT era requires analysis not only of technology and institutional design but also of social structures within ecosystems and industries and changes in technological frames.

Both Industry 4.0 and Society 5.0 are in the process of spreading concepts and reference architecture. Each reference architecture has elements that realize data sharing and cooperation between organizations, such as an integration/data federation layer [74,75]. Only a few use cases and related technological specifications have already been implemented based on such policies. Therefore, verification of the issues examined in this paper is an issue for the future, which I would like to continue to analyze.

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standards

Article

Voluntary Sustainability Standards: State of the Art and Future Research

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Abstract: In this feature paper, we introduce voluntary sustainability standards (VSS) and canvas the research that has been conducted on VSS from different academic disciplines. We identify four main areas of research on VSS and explore them. First, we focus on research on the institutional design of VSS, which highlights the diversity among VSS. Next, we explore studies that try to assess the impact of VSS on key sustainability dimensions. Third, we zoom in on studies that analyse the uptake or adoption of VSS. Finally, we focus on the interaction between VSS and public policies. For each of the four areas, we summarise the main research findings and identify opportunities for future research.

Keywords: voluntary sustainability standards; effectiveness; impact; adoption; design; institutionalisation

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1. Introduction

Standards come in many forms and shapes. In this contribution, we focus on what has been more recently referred to as Voluntary Sustainability Standards (VSS), also called sustainability certificates, eco-labels or private standards. In this paper, we aim to provide the state of the art on VSS research by focusing on selected key research areas. For each research area, we summarise the main research findings and identify main avenues for future research.

There is no fixed definition of VSS, but the United Nations Forum on Sustainability Standards (UNFSS) defines them as "standards specifying requirements that producers, traders, manufacturers, retailers or service providers may be asked to meet, relating to a wide range of sustainability metrics, including respect for basic human rights, worker health and safety, the environmental impacts of production, community relations, land use planning and others" [1] (p. 4). VSS are considered as a significant private, market-based transnational governance instrument to pursue sustainable development. VSS initiatives have procedures to develop and set standards on a wide range of sustainability issues, and have systems in place to assess and monitor conformity with standards. Often, VSS use independent third parties to perform conformity assessments. They also issue certificates to their adopters in case of compliance and allow them to label their products accordingly. Well-known examples of VSS include Fairtrade International, Rainforest Alliance and the Forest Stewardship Council. Over the past few decades, VSS have proliferated [2]. Depending on the source used, the number of existing VSS globally ranges between 300 and 500.

VSS have received significant scholarly attention and many studies have been published on the topic in various academic disciplines, from sociology, political science, international relations and law to development studies, (agricultural) economics, geography, anthropology, forestry and ecology/earth sciences. In this paper, we aim to take stock of some of this research and identify possible avenues for future research. We organise the paper around four main areas of research that can be identified in the academic literature on VSS: the design of VSS and how they operate, the effectiveness of VSS in terms of impact on key sustainability dimensions, the effectiveness of VSS in terms of adoption and uptake, and finally, the institutionalisation of VSS in public policy. For each area, we identify the main research lines and findings and propose avenues for future research in order to better understand the potential and limitations of VSS as governance instruments for sustainability.

2. Institutional Design of VSS

Several studies have been published on understanding the diversity of VSS as institutions. Many explore the variation in the institutional design of VSS, with a specific focus on their standard-setting process as well as the enforcement of standards. Four streams of research highlight different aspects of VSS institutional design.

A first and early stream of research focused on the legitimacy of VSS as transnational governance instruments. To conceptualise and analyse legitimacy in relation to VSS, many researchers build on the work by Scharpf [3], who introduced the notions of input and output legitimacy. Input legitimacy focuses on the rule-making or standard-setting process and can be assessed by examining whether standards are developed according to a set of procedural requirements, such as representation of relevant stakeholders, inclusiveness, transparency and deliberativeness [4]. This line of research has particularly focused on which actors are involved in the standard-setting process. Some authors argue that VSS are remarkably democratic and inclusive in standard-setting [5], while others are more sceptical and critical, and highlight that key actors such as producers are hardly represented in the standard-setting process [6]. Output legitimacy relates to the degree to which decision makers can be held to account after decisions are made. Output legitimacy echoes the notion of "accountability as responsiveness" [7–9], which, as Gulbrandsen describes, focuses on the "relationship between the standard organisation and various stakeholders" [8] (pp. 566–567). This notion helps capture the degree to which "power wielders" meet "the expectation of relevant constituencies", accept "answerability on the disposal of their power", and act upon "criticisms or demand made of them" [8] (p. 567). To analyse output legitimacy, researchers have focused on complaint systems of VSS as accountability mechanisms [10]. Some researchers criticised these approaches to legitimacy as they tend to leave out questions related to the broader societal acceptance of an organisation's policies, structures and operations [11]. This has been addressed by scholars using a more sociological approach to legitimacy and has led to assessing the attitudes and perceptions of the communities in which the institution in question operates. With respect to VSS, this form of legitimacy is considered particularly important since private transnational governance systems do not possess any form of de jure (legal) legitimacy and must in effect more actively seek social support and recognition from a wide variety of members, stakeholders and observers [11–13]. These approaches have been applied to several VSS [7,14].

A second stream of research focuses on the substance of standards and analyses on what social, economic and environmental aspects standards are set and how stringent these standards are [15]. This line of research also includes a focus on which international norms, conventions and agreements these standards are based on. Concerning the latter, some authors argue that VSS are firmly rooted in existing international law and, in this way, do not create new rules or commitments but operationalise existing international commitments [16]. This stream of research also focuses on the debate which results in standards' dilution or weakening on the one hand, and standards' strengthening on the other hand, with a specific focus on corporate co-option leading to greenwashing [17–19].

A third stream of research focuses on how standards are enforced. Here, a significant body of literature discusses the use of independent third-party auditing, highlighting the many deficiencies in the audit approach [20–22]. Other scholars have complemented this line of research by focusing on another enforcement tool, namely the use of complaint and grievance mechanisms by VSS to continuously monitor compliance with standards [10,21]. Concerning audits, studies focused on different aspects. First, the quality of information on compliance with standards in auditing has been questioned since auditing leads to standardisation and routinisation resulting in auditors executing a "quick job" and missing crucial information [22,23]. Some observers [20] also argue that there is an inherent conflict of interests (as auditors are paid by standards adopters) which results in auditors having incentives to underreport practices and give in on the stringency of their audit reports in order to maintain clients. In addition, audits are only performed sporadically. Due to the dynamics in value chains, it is impossible to comply with all requirements and standards [20]. The deficiencies of the audit system led to the development of additional forms of monitoring and conformity assessment with a specific focus on complaint and grievance mechanisms. In order to provide continuous monitoring, one needs multiple "eyes" or auditors who are constantly available to monitor on-the-ground conditions. Hence, some authors have argued that dispute or complaint systems provide for "second-order monitoring" [24] and could strengthen the enforcement potential of VSS [10,25].

A fourth stream of research seeks to bring these elements together and looks at how different components of institutional design combine in the context of specific VSS or provide a comparative analysis of several VSS on their institutional design [26–28]. This line of research highlights that there is significant variation on how VSS are designed in relation to how standards are set, how ex ante conformity is assessed through audits, whether or not they use complaint systems and how transparent they are. This diversity shows that not all VSS are equal in terms of design and, ultimately, effectiveness. In this stream of research, researchers have also tried to understand what influences the design of VSS. Recently, Van der Ven [29] argued that the use of VSS by large consumer-oriented retailers influences the design and credibility of VSS since VSS targeting these firms specifically want to insulate them from critical scrutiny. Hence, they develop stringent systems to provide more reassurance to firms that they are complying with sustainability commitments through their value chains.

For future research on the institutional design of VSS, we propose two main avenues. First of all, little research has focused on how VSS change over time and develop new forms of standard-setting and standard implementation. The initial governance model of VSS largely relied on a structure in which VSS kept arms-length relationships with certificate holders in order to preserve independence and foster compliance with standards. Conformity with standards was often assessed by independent third parties in order to ensure compliance. Over time, the compliance logic has been challenged with a logic of learning which might generate better sustainability impacts [30]. Little research has focused on how VSS aim to generate learning and how this has affected the ways in which they operate. Secondly, little is known about how different ways of governing standards influence sustainability outcomes. Research on governance and research on impact have largely been conducted independently. Understanding how the governance of VSS influences their impact deserves more scholarly attention.

3. Effectiveness of VSS: Impact on Sustainability Dimensions

A second major area of research constitutes studies that aim to assess the impact of VSS on the ground. This area of research aims to answer the following questions: does the implementation of VSS have the desired influence on the issues that they aim to tackle? Are VSS fit for purpose, or, put simply, do they work? Several hundreds of studies have been published on the impact of VSS. Here, we present the focus and findings of literature reviews which assess several impact studies, as well as the data available on online platforms on VSS impacts. Concerning the former, we present the reviews of the International Trade Centre (ITC), the Food and Agricultural Organisation (FAO), the Meridian Institute (MI) and Oya et al. For the latter, the data gathered by two online platforms, Evidensia and Mongabay's Conservation Effectiveness, are summarised and discussed [31,32].

Table 1 lists nine literature reviews on the impact of VSS and provides an overview of some key characteristics of the studies included in the reviews, including which VSS are most studied, on which commodities they focus on, the countries/regions most studied and the number of studies in the review. Each of these literature reviews summarises studies that use different methodological approaches, from qualitative approaches to semi-experimental quantitative approaches.

Table 1. Overview of the characteristics of the studies under review.

Review	VSS	Countries	Commodities	No. Studies
ITC-GVCs [33]	Fairtrade	Kenya South Africa Zambia	Coffee Flowers Fruits and vegetables Forestry products	54
ITC-Producers [34]	Fairtrade Organic	Costa Rica Uganda Kenya	Coffee Forestry	56
ITC-Interplay [35]	Not specified	Not specified	Not specified	78
ITC-Context [36]	General Fairtrade FSC	Multi-regional/global Latin America Africa	General Coffee Forestry products Fruits and vegetables	59
FAO [37]	GLOBALG.A.P. Fairtrade Organic	Kenya Mexico Peru Costa Rica Uganda	Coffee Horticulture	123
MI-Agri [38]	RA RSPO	Colombia Indonesia Ethiopia	Coffee Palm oil	16
MI-Forest [38]	FSC	Southeast Asia Latin America Africa	Forestry products	10
MI-Fish [38]	MSC ASC	Vietnam Australia Mexico Canada	Marine fisheries Aquaculture fisheries	6
Oya et al. [39]	Fairtrade	Latin America Africa	Coffee	43

Overall, Table 1 shows that studies mostly focus on agricultural commodities and forestry in Sub-Saharan Africa and South America and tend to concentrate only on a limited number of VSS. All these studies focus on different sustainability impacts. The results point in different directions.

The Meridian Institute [38] reviewed the literature concerning conservation and environmental impacts of agricultural, forestry and fisheries VSS. Studies in Ethiopia and Colombia showed reduced deforestation rates on farms and plantations certified by Rainforest Alliance (RA) and RSPO. However, the studies conducted in Brazil and Indonesia did not report a significant effect. Furthermore, enhanced plant biodiversity was recorded on certified farms in Ethiopia and several Latin American countries. Overall, 50% of the impacts are positive, while the other half show no significant effect of agricultural certification on conservation issues. With regard to fisheries certification, a limited number of studies on the MSC found an improvement in the status of the harvested population over time due to certification.

Concerning socio-economic impacts, Oya et al. [39] find positive impacts on prices, incomes from certified production and schooling, but also that the different VSS under study are not equally effective. Their analysis does not bring any clarity on the overall effect of certification on socio-economic issues across different certification schemes and commodities, making it impossible to draw general conclusions. Similarly, mixed results are reported in the studies of the ITC [33,34] and FAO [37]. The latter highlights that the adoption of VSS can improve smallholders access to Global Value Chains (GVCs) and to markets. This, however, does not guarantee immediate benefits. Long-term spill-over effects in terms of competitiveness, such as the possibility to sell more non-certified products through market integration, can enhance profitability.

To assess the impacts of VSS more systematically, recent databases have been made available, of which Evidensia is the most prominent one. Evidensia is an online platform founded in 2019 by ISEAL Alliance, Rainforest Alliance and the World Wildlife Fund, and gathers all the relevant and reliable primary and secondary literature about the impact of market-based sustainability tools and supply chain initiatives on multiple sustainability issues [40]. The platform provides the option of accessing the results of impact studies visually with the "Visual Summaries". This tool makes it possible to gain insight into the number of specific outcomes, reported concerning a multitude of sustainability issues [41]. The Visual Summaries provide information on the environmental and economic impact of certification by several VSS applied to the agricultural and forestry sectors. To evaluate VSS environmental impact, issues such as carbon sequestration, soil erosion or species richness are evaluated. For example, if a study shows that the species richness in a certified region is significantly higher than in an uncertified region, a positive impact on species richness due to certification is shown in the Visual Summaries. Evaluating the economic impact is performed by focusing on the household income, price premiums, product income and yield. For example, when a study shows a significant increase in the household income of a household that works in certified agriculture compared to conventional agriculture, a positive impact is shown in the Visual Summaries. The regions in which the impacts are measured are primarily Latin America; East, Central and West Africa; and East, South and Southeast Asia. Only two of the included studies executed their research in Europe, and none in North America. To provide comparable and credible results, the studies are selected against strict quality criteria concerning research design (statistical-based analysis which allows for isolating the effects of VSS and which compares a treatment group (VSS-certified) with a control group (not certified)) and need to be recent (not older than 10 years) [41]. The database contains information on almost 450 impacts. For each of them, the database reports whether it is a positive impact (the VSS group performs better than the control group), a neutral impact (there is statistically no difference between the VSS group and the control group) or a negative impact (the control group performs better than the VSS group).

Of the 447 impacts listed in the Visual Summaries, 205 are positive and 211 are neutral. Only 31 of the impacts appear to be negative. This trend continues when looking at the distinct impact categories. Table 2 reports 94 positive and 93 neutral impacts on environmental issues, and only nine negative impacts. For the socio-economic impact of the studied VSS, 111 positive impacts and 118 neutral impacts are found, in contrast with 22 negative impacts which are mainly related to increased costs linked to obtaining certification.

Table 2. Number of positive, neutral and negative impacts of VSS per issue category.

Issue Category	Positive	Neutral	Negative
Environment	94	93	9
Socio-Economic	111	118	22
Total	205	211	31

In Table 3 and Figure 1, the impacts extracted from studies that focus on a single country are shown. By filtering these, 379 out of a total 447 impacts remain. The countries in which most impacts were recorded are Nicaragua, Colombia, Ethiopia and Uganda. It is noteworthy that few studies have been conducted in Europe and the United States.

Table 3. Number of positive, neutral and negative impacts of VSS per country.

Country	Positive	Neutral	Negative
Brazil	4	5	1
Cameroon	0	1	0
Chile	3	1	0
China	2	3	1
Colombia	28	20	1
Côte d'Ivoire	8	6	0
El Salvador	3	2	0
Ethiopia	16	15	3
Gabon	5	4	0
Ghana	2	7	0
Guatemala	1	0	0
India	13	13	2
Indonesia	7	12	1
Kenya	11	9	2
Madagascar	2	0	0
Malaysia	0	2	2
Mexico	7	8	0
Nicaragua	21	27	5
Pakistan	7	3	1
Peru	5	13	2
Portugal	1	1	0
Rwanda	0	2	1
Sweden	0	5	0
Thailand	2	2	0
Uganda	17	10	6
United Republic of Tanzania	4	2	0
Vietnam	4	5	0
Total	173	178	28

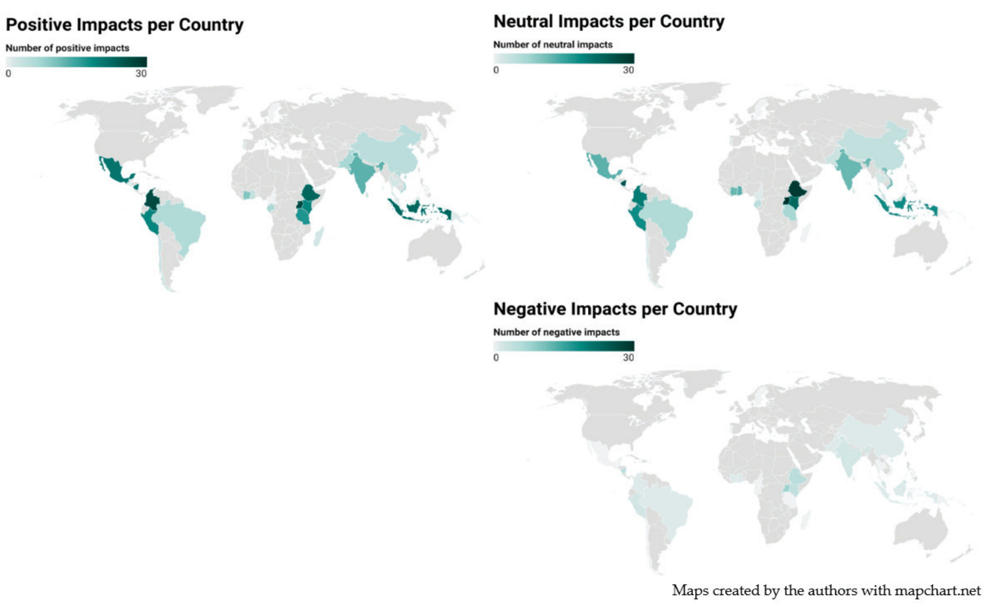

Figure 1. Global distribution of the positive, neutral and negative impacts of VSS.

The impacts that are extracted from studies that focus on a single VSS are isolated and listed in Table 4, and 228 out of the total of 447 impacts of the platform remain. The three most studied VSS, i.e., with most impacts listed, are RA, UTZ and the FSC. RA seems to have an overall positive impact, with 41 positive impacts, compared to 23 neutral ones and one negative one. For the FSC, the number of positive and neutral impacts is comparable, with 15 positive impacts and 13 neutral ones, and no negative impact. For UTZ, the neutral impacts recorded are almost double the positive ones, with 11 positive impacts and 21 neutral ones.

Table 4. Number of positive, neutral and negative impacts per VSS.

VSS	Positive	Neutral	Negative
4C Association	2	6	0
Better Cotton Initiative (BCI)	7	3	1
Bird Friendly	6	6	0
Eurep GAP	1	1	0
Fairtrade International	5	7	1
Forest Stewardship Council (FSC)	15	13	0
GLOBALG.A.P.	6	5	0
Green Food Program (China)	0	2	0
International Federation of Organic Agriculture Movements (IFOAM)	9	11	2
Rainforest Alliance (RA)	41	23	1
Roundtable on Sustainable Palm Oil (RSPO)	3	5	2
Starbucks C.A.F.E. practices	0	2	1
Sustainable Agriculture Network (SAN)	3	3	0
UTZ	11	21	3
Total	109	108	11

The impacts extracted from studies that focus on a single commodity are listed in Table 5, and 436 out of 447 impacts remain. About 64% of the impacts come from studies focusing only on coffee production. The number of positive and neutral impacts are equal (both 130). About 8% of the impacts of VSS in coffee production is negative.

Table 5. Number of positive, neutral and negative impacts of VSS per commodity.

Commodity	Positive	Neutral	Negative
Banana (fresh)	2	2	0
Black pepper	5	3	2
Cocoa	12	19	1
Coffee	130	130	21
Cotton (raw)	7	3	1
Forestry plantations	20	26	0
Honey	3	0	0
Lychee	2	0	0
Palm oil	3	5	2
Peas	1	0	0
Rice	11	16	1
Strawberries	1	2	0
Tea	4	1	0
Total	201	207	28

The results from the Evidensia database on the FSC specifically correspond to the results from the Conservation Effectiveness database. Conservation Effectiveness is a community-sourced platform, founded in 2016. It is a collaboration between Mongabay, a conservation and environmental science news platform, and tropical forest ecologist and conservation scientists from the University of Wisconsin [31]. Conservation Effectiveness presents the environmental, social and economic impact of certification by the FSC. The evidence typology in Conservation Effectiveness is similar to Evidensia and focuses on statistical models which can isolate impact from other confounding variables [42,43].

Conservation Effectiveness reports on 72 impacts related to the FSC. The majority of the impacts of FSC is either positive or neutral (40 positive impacts and 27 neutral impacts); only five impacts are negative. Table 6 shows that the FSC appears to have the most positive impact on economic issues such as profits, pre-logging costs or price premiums. There is approximately the same amount of positive and neutral impacts on environmental and social issues.

Table 6. Number of positive, neutral and negative impacts of the FSC per issue category.

Issue Category	Positive	Neutral	Negative
Economic	19	7	4
Environmental	12	13	1
Social	9	7	0
Total	40	27	5

What do we learn from these studies in general? When are VSS effective in achieving sustainability improvements? It is difficult to draw any general conclusions since all studies point to the fact that impacts are case-specific and vary widely. Overall, there are more positive impacts than neutral or negative ones linked to certification, but this does not hold across VSS, commodities and countries. Based on the interpretation of the results, some general observations can be made.

It seems evident that the characteristics of the VSS influence their effectiveness. The ITC found that important characteristics to achieve the objectives are the sector of focus, the legitimacy of the VSS, the balance between more general applicability and suitability for local circumstances, and the existence of clear and short-term benefits incentivising adoption, such as immediate price premiums. Oya et al. [39] suggest that the mechanism used to influence the price paid to the producer (e.g., price premiums, price floors, etc.), and whether this approach is compatible with the target sector or target commodity, is determining for VSS impact. Secondly, the conditions of eligible actors (i.e., farmers, producers) seem to be an important factor. The FAO found that the ability of the exporters and farmers to achieve compliance is highly dependent on the capacity at the farm level since entering the GVCs requires a certain level of persistence [37]. Finally, the context is a crucial factor for the impact of VSS. Consisting of factors out of the realm of control of the certification system, implementation of the same VSS can have different outcomes in different contexts [39]. Two components seem to be important concerning this context. On the one hand, the characteristics of buyers and value chains are influential factors [36]. VSS are tools to enter global value chains and the degree to which they facilitate this will also determine their impact. Based on a limited number of studies, the adoption of VSS seems to be able to facilitate access to global value chains. The structure of the value chain plays an important role in the distribution of revenues [33]. Studies also underline how the barriers to enter the value chain becomes higher for smallholders, who face more difficulties to adopt standards. Some studies also find that revenues resulting from VSS adoption are unevenly distributed along the chain and sometimes in the benefit of major buyers in the value chain, such as retailers [33].

On the other hand, the broader political and policy environment in which VSS are implemented play a role. Several studies point to the relevance of this policy "embeddedness" for the efficient implementation of VSS. Therefore, the ITC advocates for more cooperation between standard setters, public authorities, international organisations and the private sector to achieve impacts [35]. Oya et al. come to similar conclusions [39]. More qualitative studies show that the agricultural and economic policy environment is decisive for the effectiveness of VSS [39]. Recognising the interplay between VSS and public institutions, the FAO argues that national governments can support and facilitate participation and standards implementation [37]. The ITC report agrees that support is needed, particularly in the case of smallholders entering global value chains. However, it remains unclear what kind of support would be most effective in which circumstances [33].

With regard to assessing VSS impacts, we propose four areas for future research. First, a limitation mentioned across all reviews is the overrepresentation of certain countries or regions, VSS and commodities in the existing literature. This research focus was mentioned in early studies [36]. Oya et al. [39], who conducted a review several years later, still mention how the majority of studies focus on the same regions, commodities and VSS. This also becomes apparent when screening the online databases. This lack of data and the high case-specificity in this field of research makes it impossible to draw global conclusions on the impacts across all VSS and sectors. Broadening this scope to other VSS and countries would constitute the first avenue for research.

Second, the research designs, methods of data collection and indicators used are research-specific and inhibit cross-research projects comparisons. The ITC suggests the use of standardised indicators in future research in order to enhance comparability.

Third, disentangling causality remains a conundrum. The ITC [35] reports that finding causal relations remains difficult since VSS trigger a diversity of interventions over a long period. As a result, VSS interventions are interrelated with other developments, making it difficult to identify the net effect of certification on sustainability. Moreover, the review from the FAO [37] highlights the importance of disentangling causal mechanisms since most current studies do not allow for a causal interpretation. To address this conundrum, research with mixed research designs should be conducted to combine quantitative analysis with qualitative analysis based on process-tracing, with a strong focus on how VSS interventions combine and interact with other types of interventions. To assess the causal link between a certain intervention and its outcome, VSS and their respective interventions should be disentangled [39].

A last area for future research should focus on linking VSS governance and design with their impacts. Overall, impact studies highlight that some VSS have more impact than others, and that some VSS are more effective in solving some sustainability issues rather than others. However, there remains a lack of understanding about why some VSS are more effective than others and what institutional design characteristics determine impact. Governance studies and impact studies have mostly been carried out independently and the links between governance and impacts remain largely hypothesised. More research is needed to understand how the design of VSS influences their impacts.

4. Effectiveness of VSS: Adoption

A third major area of research on VSS has explored the adoption of VSS, or their uptake. Adoption can be defined as the extent to which VSS are used and is an important component of VSS effectiveness as low adoption rates constrain the potential of VSS to create impacts on the ground. In order to significantly contribute to sustainability, VSS need to diffuse widely. Research on VSS adoption has generally revolved around two different questions: (1) Where and to what extent are VSS adopted? (2) Why are VSS adopted? Studies aiming to answer the first question have assessed where and to what extent VSS are adopted based on different units of analysis.

A first unit of analysis is situated at the country level. Studies have explored the distribution of VSS across countries and the uptake of specific VSS in specific countries. Research find that all countries have VSS active on their territory, but that there is significant variation in the number of VSS present across countries and in their coverage at country level [2,44]. These studies show that country-level VSS adoption is influenced by several economic and political factors. In an early study, van Kooten et al. [45] tried to identify the country-level conditions that encourage the growth of a private regulatory environmental system to govern forests. They examined 117 countries to identify factors determining forest certification under the Forest Stewardship Council and domestic competitor schemes. Besides economic factors (forestry products exports and GDP), they identified that political (size of government, structure of the economy and freedom to trade) and social (literacy rates and the degree of suppression of women) factors also play an important role in adoption. The importance of political factors for understanding VSS adoption is also highlighted in other studies. Bartley [46], for example, in a case study of Indonesia, argues that understanding the political context of a country is important for understanding the dynamics of forest certification adoption. Similarly, a literature review of more than 100 studies argued that a necessary, although insufficient, condition for VSS adoption is the presence of national institutions to provide a supporting environment for compliance with standards and regulatory compliance [37]. These studies point to the fact that countries which have developed effective and well-functioning governance structures constitute a better institutional context for VSS adoption.

Adoption studies across countries have also focused on the question of whether adoption is occurring in places most in need of sustainability improvements. Tayleur et al. [47] focused on VSS certifying tropical commodities—which are mainly produced in developing countries—and showed that VSS are located in countries or regions most important for biodiversity conservation, but not where poverty alleviation needs are direst. These findings show a selection bias in VSS systems that excludes the poorest countries [14]. To account for this bias, Marx and Cuypers have referred to the "stuck at the bottom problem", which argues that complying with VSS requirements is more difficult for countries most in need for sustainability improvements for two reasons [48]. First, there is a governance gap between government regulations, which are typically weaker in developing countries, and VSS requirements, which are more stringent. Producers and firms in developing countries are therefore used to operate under more lenient regulations, and complying with sustainability standards demands greater changes in practices. This can involve higher production costs and the need for technical capacity and know-how. In comparison, countries where government regulations are more stringent make it easier for producers to comply with VSS. Second, only producers that have prior income or assets have the potential to adopt VSS since certification involves significant costs, and smallholder farmers are typically discriminated in VSS markets.

A second unit of analysis of the extent of VSS adoption is the distribution of VSS across economic sectors. Much research has focused on the emergence and development of VSS in specific sectors with a main focus on garment and textile sector [49,50], forestry [17,49] and different agricultural commodities such as coffee, tea and cocoa [17]. This literature points to the different factors which induced the emergence of VSS in specific sectors and also accounts for the fact that one can observe many VSS in specific sectors. This line of research has also focused on the competition between standards in economic sectors and the relative lack of convergence and cooperation between VSS [51]. Based on an analysis of the ITC Standards Map and the Ecolabel Index, researchers also focused on the distribution of VSS across sectors [2]. Research points to great disparities in the number of VSS across sectors which result from differences in the structure and complexity of some global value chains and from the high price volatility for some commodities such as rubber, which make it difficult to set up VSS [52] (pp. 34–35).

Third, research has explored the extent of VSS uptake at commodity level by analysing both the share of production land certified globally and the share of production volume certified. These studies mainly focus on agricultural commodities and forests. According to different estimates, less than 2% of global cropland is currently certified, but research shows that this proportion is increasing over time, with an annual increase of about 11% [53,54]. However, this low overall certification percentage hides variation between commodities. For example more than 25% of the global production volume of coffee and of cacao are certified, and more than 10% of global forests [55].

Common to these three strands of research on different units of analysis is the assumption that VSS adoption is growing rather steadily over time and across VSS. However, there are disparities in adoption across VSS, with some VSS being more adopted than others. Several interplaying factors can explain why some VSS diffuse more widely than others, including the net benefits they provide to adopters of standards [56–58], their recognition by governments [59,60] and their stringency [29,61,62]—although a study by Castka and Corbett finds no link between stringency and adoption [57]. Besides, individual VSS can also experience fluctuations and even decline in their adoption. Research on the dynamics of VSS adoption and their determinants is lacking.

A second strand of research on VSS adoption has aimed to provide answers as to why VSS are adopted by exploring motives for adoption by (1) producers or firms along global value chains (e.g., producers, buyers, retailers), (2) consumers and (3) governments (see next section).

Firstly, studies have put forward five major motivations for producers and firms along global value chains to take up certification. First, producers and firms adopt VSS as a means to mitigate reputational risks [63–65]. With the increase in civil society campaigns and boycotts against firms whose activities bear adverse consequences on socioeconomic or environmental conditions, firms adopt VSS as proof of compliance with sustainability practices to protect their reputation. Second, VSS can yield a price premium for producers or firms as on some markets, certified products can be sold at higher prices [48,65]. However, research has also highlighted that price premiums are not guaranteed and depend on consumers' willingness to pay, on the presence of substitute goods and on oversupply of certified products [62,66]. In addition, even in the existence of a price premium, producers and suppliers do not always reap the benefits of certification as powerful actors in the value chain capture the premium [19]—what Ponte refers to as the "sustainability-driven supplier squeeze" [67]. Third, producers or firms use VSS as means to enter global value chains and increase their access to higher value markets. VSS can be considered as a tool to transfer information, or as a signalling mechanism to inform consumers, governments and other business actors about the sustainability of products or production methods [58,66]. VSS can increase market access via two channels: (a) as a differentiation mechanism, they can improve access to environmentally and socially sensitive markets [68]; and (b) they can provide market access when this latter is conditional on compliance with specific sustainability criteria by serving as proof of compliance with such requirements [68,69]. Fourth, VSS enable firms or producers to innovate. VSS constitute a knowledge transfer and learning mechanism by means of which those actors can implement more sustainable practices, sometimes allowing for efficiency gains [30,68]. Fifth and last, adoption of VSS by producers or firms along global value chains can be driven by individual ethical values and commitment to sustainability [69,70]. Yet, research shows that reputation management, price premium and market access remain the strongest drivers of VSS adoption [58]. In addition, the literature has highlighted an important shortcoming of VSS adoption along global value chains. VSS adoption by large buyers and retailers who have significant bargaining power and impose certification on their suppliers down the value chain can foster wider adoption of VSS [66,67]. However, this also contributes to the exclusion and marginalisation of suppliers—typically smallholder farmers in developing countries—who are not able to comply with VSS requirements [37,71,72].

Secondly, research have explored VSS adoption by consumers and have highlighted several challenges. VSS adoption by consumers refers to their purchase of certified products. This is driven by their sensitivity to sustainability issues related to production and consumption—what is called ethical consumerism—and whether such sensitivity translates into more sustainable purchasing practices, thus creating a consumer market for VSS. In the literature, the existence of a large consumer market for VSS remains debated. Increases in market shares of certified products in some sectors argue in favour of the existence of such market. For example, one can observe a strong increase in a number of certified products. In the Netherlands, 45% of the coffee sold on the Dutch market, in 2010, is certified, compared to only 2.9% in 2001 [73]. A similar increase, although not as outspoken, can be observed for other products. However, whether consumer demand is a strong driver for VSS adoption is currently hotly debated in the context of ethical consumerism. In a collection of papers by Dara O'Rourke [74] and the responses by several others, it emerges that there is indeed a consumer market for sustainable products, but how large this consumer market is remains unclear. Brenton [75], for example, raises doubts about the strength of consumer demand to support voluntary standards. He examines the political motivations underlying ethical consumption, such as its relationship to other forms of political activism and how existing values interact with consumption choices, and argues that many of the factors involved in consumer decision making are inconsistent with the assumptions made by private economic governance schemes in attempting to harness consumer power. Indeed, other studies show that individual consumers' demand for VSS depends on multiple factors including age, nationality, motivation, past experience with VSS, scepticism towards VSS, level of knowledge about VSS, need, accessibility, affordability, product performance or force of habit [76,77]. Another study highlights that there is demand for certified goods and that consumers (mainly in Europe and North America) will consciously choose for certified goods, but only if the price remains the same [78]. In addition, studies show that the proliferation of VSS on consumer markets has generated confusion among consumers about the missions of, differences between, and effectiveness of VSS [79,80]. This has undermined consumers' trust in VSS. Overall, findings highlight an "attitude–behaviour gap", meaning that the expression of consumers' willingness to buy certified products at higher prices does not necessarily materialise into more sustainable purchasing behaviours [78,81]. As a result, research shows that there is an oversupply of certified products in some markets as consumer demand has not kept up with supply, and hence, some certified products need to be sold as non-certified, as is the case in the coffee sector, for example [53].

Six main areas for future research on VSS adoption can be identified. First, significant research has investigated where VSS are active and which factors contribute to the uptake of VSS. Most researchers focus on explaining the uptake and growth of VSS and assume that the adoption dynamics of VSS are linear, i.e., that once a VSS is adopted in a country, it remains there and increases its coverage. However, in a recent paper focusing on the adoption of the FSC, Depoorter and Marx [82] show that VSS adoption dynamics are not linear and highlight several adoption dynamics, including saturation, stagnation and decline. Understanding these different dynamics constitutes a new area of research.

Second, there is a relatively sufficient understanding of some of the economic, political and social factors that are related to the adoption of VSS and the mechanism by which they induce VSS uptake. Yet, it is less clear how other factors, such as good governance and political context, influence VSS adoption. For example, we know countries that score well on good governance are hypothesised to have higher degrees of VSS adoption. However, the operationalisation of what exactly is understood under political institutional context and governance structure remains vague. As the FAO [37] notes, far more research is needed in this respect.

Third, concerning VSS adoption across economic sectors, most research has focused on the emergence of VSS in specific commodity sectors and the diffusion of the certification model over different sectors, but less research has focused on the non-emergence of VSS in other sectors. There are many economic sectors and commodities for which no VSS are available. Hence, understanding the barriers to VSS emergence requires more research.

Fourth, research is needed on how to foster VSS adoption in areas most in need for sustainability improvements. Research has shown that VSS are mostly active in countries with well-functioning governments and in regions that are important for biodiversity preservation, but not in areas most in need of poverty alleviation [47]. Hence, research is needed on how to scale up VSS adoption in a more strategic and targeted way. In this regard, case-based research could help understand how VSS can be improved and adjusted to specific contexts, and what complementarities they could present with other relevant actors to maximise sustainability improvements, e.g., through hybrid governance arrangements [83].

Fifth, research has highlighted that the adoption of VSS by powerful actors along global value chains can help diffuse them, hence contributing to their effectiveness. Future research should explore whether such diffusion channel is desirable and how to ensure that more vulnerable actors are included in certification dynamics and benefit from it.

Lastly, further research needs to be conducted on how to foster and harness consumer demand for VSS and on the impact of recognition systems in that respect. Some organisations, such as the European Commission, are launching initiatives to reduce consumer confusion about VSS through recognition systems [84]—i.e., endorsing credible VSS based on minimum criteria. The potential of such recognition systems to foster consumer demand for VSS remains to be explored.

5. Institutionalisation of VSS

A fourth area of research which is emerging focuses on the so-called institutionalisation of VSS in public policy [83,85–87]. Institutionalisation of VSS in public policies occurs when references and functions of VSS are integrated in public policies. This integration of VSS can take different forms in different policy arrangements.

First, D'Hollander and Marx [88] have shown that VSS play a role in sustainable public procurement. The term "sustainable public procurement" is used to refer to socially and environmentally friendly public procurement policies. The latter implies that governments, from the local to the national level, buy goods and services which that with sustainability requirements. Given the purchasing power of governments, sustainable public procurement can have significant impact on a large variety of products. VSS play a specific and increasingly significant role since they are often integrated into the operationalisation of sustainable public procurement practices [88,89]. Second, VSS are increasingly referred to in the context of trade policy and efforts to make trade policy more sustainable. The UNFSS [2] analysed the degree to which one can find references to VSS in bilateral and multilateral free trade agreements. Marx [90] also explored ways in which VSS can be integrated in unilateral trade instruments such as the Generalised Scheme of Preferences. Third, some scholars have focused on the integration of VSS in specific regulations. In this context, researchers have focused on the integration of VSS in the EU Timber Regulation and analysed a new form of governance which is labelled by Jonathan Zeitlin and colleagues as "experimental governance" [91]. Attention has also gone to the EU Renewable Energy Directive, which established a set of sustainability criteria for biofuels, including environmental and social criteria. In order to ensure that biofuels are compliant with these criteria, recognised VSS provide proof of compliance with those criteria. The directive explicitly refers to VSS, and several scholars have analysed the potential and limitations of integrating VSS in public policy with the renewable energy directive as a case study [92,93].

Besides analysing how VSS are integrated in public policy based on specific case studies, some scholars have tried to understand what is driving this integration, while other scholars have tried to more systematically categorise this institutionalisation. Concerning the former, a study by Renckens [94] focuses on the integration of VSS in European Union policy making on organic agriculture, biofuels, fisheries and fair trade, and shows that in some cases, VSS are actively pursuing a strategy of being integrated in public policies which is accepted by policy makers, while in other cases, policy makers are more reluctant to integrate VSS in public policy. Drawing on European Union policy making on organic agriculture, biofuels, fisheries and fair trade, Renckens exposes the political and economic conflicts between private and public rule-makers and the strategic nature of regulating sustainability in a global economy. Based on these cases, he develops a new theory of public–VSS interactions focusing on the economic benefits to domestic producers and the degree of fragmentation of VSS schemes.

Concerning the categorisation, Lambin et al. [81] provide an overview of how private governance instruments such as VSS are integrated in public policy in the context of land-use management. They characterise public–private interactions as being either complementary, substitutive or antagonistic. "Complementary" involves states offering an enabling and supportive regulatory environment for VSS operations, or allowing them to fill in policy gaps; "substitutive" refers to governments absorbing existing VSS into public policies or laws by transforming private rules into public ones; and "antagonistic" refers to public and private rules prescribing conflicting practices. Marques and Eberlein [86] distinguish five types of public–private interactions of which two, "replace" and "reject", focus on government regulation replacing private regulation or outright rejecting private regulation. The other three types describe ways in which public regulation engages more positively with VSS. First, VSS can act as "substitutes" for public rules on matters which states are unable or unwilling to regulate, similar to Lambin et al.'s "complementary" role. Second, states can "adopt and support" VSS by acting as clients of certification for state-led production operations, providing administrative or financial support to domestic firms to comply with VSS, politically endorsing VSS or enacting policies that recognise VSS as proof of compliance with public requirements. Third, states can build on existing VSS and "repurpose" them to better fulfil public objectives.

We suggest two main topics for future research on the institutionalisation of VSS. First, the integration of VSS in public policies raises the question of how rule makers distinguish credible from non-credible standards. We know that many VSS are available for the governance of certain commodities. We also know that these VSS differ in institutional design, credibility and ultimately effectiveness. If one integrates VSS in public policies, one must ensure that one only integrates effective VSS. To distinguish credible from non-credible VSS, public policy makers must establish recognition systems. More research must be conducted on how these recognition systems are designed and what their impact is.

Second, little research is conducted on the impact of the integration of VSS in public policies on VSS themselves, both in terms of substantive standards which are covered, as well as with regard to the implementation and enforcement of standards. It could be hypothesised that VSS will change due to their integration in public policies. Little is known about what this change entails. The latter is especially relevant in the context of the emergence of new human rights due diligence regulations, which will impact producers all over the world [95]. These due diligence regulations, which are emerging in many countries, partially rely on VSS to ensure compliance with due diligence requirements.

6. Conclusions

Voluntary Sustainability Standards have emerged as a transnational governance tool in the 1990s. Although one can find earlier examples of VSS, the use and spread of VSS across commodity sectors to transnationally govern global value chains really took off in the 1990s and early 2000s. As a result, research on VSS started to emerge. More than 20 years after early studies on VSS, the research community focusing on VSS has grown and consolidated. Researchers from various disciplines including sociology, political science, international relations, law, development studies, (agricultural) economics, geography, anthropology, forestry and ecology/earth sciences have started to conduct research on VSS. This has led to an interdisciplinary research community exploring the different dimensions of research on VSS.

In this contribution, we aimed to map the major trends in research on VSS and identify some of the key findings. For each of the four trends (design, impact, adoption and institutionalisation), we propose different avenues for future research.

First, research has focused on understanding VSS as a new form of global governance in terms of how they are designed. Overall, this area of research has pointed to the high diversity in the institutional design of VSS. It calls for further research on how the design of VSS is evolving over time, and how it influences VSS impacts. Next, studies have analysed VSS effectiveness along multiple dimensions. Most prominently, research focused on the impact of VSS on a number of sustainability issues (environmental protection, labour rights, poverty alleviation, etc.) and on the adoption of VSS across countries, actors (consumers and business) and commodities. On the former (i.e., impact), research finds limited and context-specific evidence of the impacts of VSS, and highlights a lack of diversity in terms of countries, commodities and VSS studied, stemming from insufficient data availability and quality. This calls for more diversity in case study selection in terms of countries, commodities and VSS, as well as for the application of more diverse research designs, methods and data collection in order to address significant data gaps. On the latter (i.e., adoption), research finds unequal adoption of VSS across countries, sectors and commodities and identifies shortcomings in the motivation for business and consumers to adopt VSS. Further research is needed on the dynamics of VSS adoption, and on how to foster higher adoption in areas most in need for sustainability improvements as well as by consumers. Finally, research started to focus on the institutionalisation of VSS, in other words, how they are integrated in public policies with regard to trade, natural resources governance and public procurement among other policy areas. Exploring ways to distinguish credible VSS from non-credible ones and studying the impact of institutionalisation on VSS design and content constitute avenues for future research in this area.

Further research in these four areas is crucial to improve our understanding of the potential and limitations of VSS and the conditions under which they can contribute to sustainability. As VSS have become a mainstream governance instrument but are often criticised, research can not only help manage expectations about what VSS can and cannot achieve, but can also advise in optimising their design and inform policy making in the context of their increased integration in public policy.

We hope that this contribution further triggers interest in research on voluntary sustainability standards as one of the major areas of standards research.

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Screening for Noise-Induced Hearing Loss among Palm Oil Mill Workers in Peninsular Malaysia: A Comparison across Noise Exposure Levels

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Abstract: Background: Palm oil mill workers in Malaysia are exposed to hazardous levels of noise in the workplace, and thus are at risk of developing noise-induced hearing loss (NIHL). In 2019, Malaysia introduced a new noise regulation, which reduced the level of permissible noise exposure. Objectives: This study aims to determine the prevalence of NIHL among palm oil mill workers based on screening data and assess the effects of different noise exposure levels on NIHL. Methods: A cross-sectional study was conducted by analyzing data from noise risk assessment reports of selected mills and screening audiometric data from workers. NIHL was defined as bilateral high-frequency hearing loss. Results: The overall NIHL prevalence was 50.8%. Noise exposure level and age were significant predictors of NIHL among the workers. The risk of developing NIHL was high even for workers who were not categorized in the high-risk group. Conclusions: In view of the findings, a precautionary approach is needed when evaluating the risk of NIHL in the study population. Vulnerable groups of workers must be protected from occupational noise hazards through the implementation of effective hearing conservation programs in the workplace.

Keywords: noise-induced hearing loss; noise legislation; palm oil; Malaysia; exposure level

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1. Introduction

Occupational noise-induced hearing loss (NIHL) has long been identified as a major occupational health issue. Chronic exposure to noise levels exceeding 85 dBA is a known risk factor for developing NIHL [1,2]. Acute NIHL can also occur during occupational exposure to loud impulsive noise, for example, in soldiers when a gun is fired [3]. The impact of NIHL is not only limited to hearing disability, but it can also lead to social isolation, loss of productivity, mental health issues, as well as an increased risk of injuries [1].

The global prevalence of disabling hearing loss was estimated to be 6.12% in 2018 and is projected to grow to 9.6% by 2050, with noise exposure being one of the major contributors to this problem [4]. Rapid industrialization, especially in Asian countries, has caused a surge in the population of workers exposed to hazardous levels of noise at the workplace [5]. Malaysia as a developing country has embraced industrialized agriculture on a massive scale, enabling it to become one of the biggest producers of palm oil in the world [6]. In 2019, the total oil palm plantation area in the country was 5.9 million hectares, producing almost 20 million tonnes of crude palm oil. Currently, there are more than 450 palm oil mills in operation throughout Malaysia [7].

The production of crude palm oil begins with the harvesting and transporting of fresh fruit bunches to mills, which are usually located in the vicinity of the plantation areas. The fruit bunches are sterilized using steam before undergoing the threshing process to strip the fruitlets from the bunches. Next, the fruitlets are transported through the digester and the press machine to extract crude palm oil. The pressed digested fruit are further processed to produce fibers, palm shells and kernels [8]. The entire operation of palm oil mills has been documented to generate hazardous levels of noise due to the processes and machineries involved, exposing the workers to noise levels exceeding 85 dBA [9–12].

Since 1989, employers in Malaysia have been mandated by law to identify workers who are exposed to noise exceeding the action level of 85 dBA, and to carry out necessary interventions to protect their hearing. The permissible exposure limit (PEL) was defined as an equivalent continuous sound pressure level of 90 dBA, a maximum noise level of 115 dBA, or a peak sound pressure level of 140 dB [13]. In 2019, a new regulation on noise exposure was enforced. The term "excessive noise" was introduced, defined as a daily noise exposure level exceeding 82 dBA, daily personal dose exceeding 50%, maximum sound pressure level exceeding 115 dBA, or peak sound pressure level exceeding 140 dBC. The noise exposure limit (NEL) is similar to the previous PEL, but with a reduced daily exposure level of 85 dBA. Workers exposed to noise exceeding the NEL are required to undergo annual audiometric tests. The new regulation also made it mandatory for employers to demarcate areas with noise exceeding NEL as "Hearing Protection Zones" [14].

Numerous studies have described age and work duration as significant predictors of NIHL [15–20]. NIHL is also associated with other factors, including leisure time exposure, chemical exposure, vibration exposure, cigarette smoking, education level, hypertension, and the use of hearing protection devices [16,21–24].

Taking into account the high level of noise at the mills and the implementation of the new regulation, our study seeks to estimate the prevalence of NIHL among palm oil mill workers using data from screening audiometric tests and to assess the significance of different noise exposure levels as a predictor of NIHL.

2. Materials and Methods

2.1. Study Population and Sampling Method

This cross-sectional study was conducted in the eastern region of Peninsular Malaysia from June 2019 until June 2020. The study duration coincides with the transition period from the previous 1989 noise regulation to the newly enforced 2019 noise regulation. Using a random number generator, ten mills were selected from a list of licensed palm oil mills in the region and received an invitation to participate in the study. Each mill employed about 50 to 100 workers, made up almost entirely of local residents.

Sample size was calculated based on a small-scale study involving workers in a palm oil mill in the neighboring country of Indonesia. The study reported that 35% of workers were detected to have NIHL, according to their audiogram results [12]. With a 5% margin of error at 95% confidence level, the estimate sample size was 350. Anticipating a 20% incomplete data percentage, a total of 420 workers was needed for this study. Taking into consideration the need to assess individual workers according to their respective noise exposure levels, sampling was performed by randomly selecting palm oil mills and including all the workers from those mills.

The inclusion criteria were employees aged 18 and above with a work duration of at least 6 months who had undergone annual audiometric test within one year from the date of data collection. We excluded those who had been diagnosed with any hearing-related medical condition or sustained injury that would have directly affected his or her hearing condition.

2.2. Study Subjects

Nine mills agreed to participate, with a total of 522 workers. Although annual audiometric tests are only mandatory for workers exposed to noise exceeding the noise exposure limit, all of the workers from these nine mills regardless of noise exposure level underwent screening audiometric tests in either 2019 or 2020. A total of 28 workers were excluded: 8 due to hearing-related medical conditions, and 20 due to work duration of less than

6 months. To ensure confidentiality, audiometric data were deidentified and each worker was assigned a combination of letters and numbers as identifiers for data analysis purposes.

2.3. Noise Assessment Report (NRA)

Due to the excessive noise generated during operation, palm oil mill employers are required to appoint a licensed noise risk assessor to conduct a yearly noise risk assessment. The equipment used in this assessment, such as sound level meters and noise dosimeters, was to be calibrated within one year of the assessment. Sound level meters are required to comply to the requirement for IEC 61672-1, class 1 or class 2 instrumentation. Noise dosimeters including a microphone and the associated cable are required to comply to the requirement specified in IEC 61252. The noise dosimeter setup was as follows: criterion level of 85 dBA, threshold level of 80 dBA, exchange rate of 3 dB, time constant set at "slow", and peak level of 140 dBC. Sound level calibrators are required to comply with the requirements specified in IEC 60942, class 1. The NRA include the identification of similar exposure groups, noise area mapping, and personal noise exposure evaluations for relevant workers according to their workstations. Workers are provided with hearing protection devices and are expected to wear them whenever they enter the designated hearing protection zones [25].

Based on the NRA, we categorized the workers into three exposure groups: low, moderate and high exposure. Workers stationed in office buildings away from machinery noises were put into the low exposure group. The moderate exposure group comprised workers who were exposed to excessive noise that did not exceed the NEL. Workers exposed to noise exceeding the NEL were categorized into the high exposure group. Excessive noise was defined as "daily noise exposure level exceeding 82 dBA or daily personal noise dose exceeding fifty percent, or maximum sound pressure level exceeding 115 dBA at any time, or peak sound pressure level exceeding 140 dBC". Noise exposure limit (NEL) was defined as "daily noise exposure level exceeding 85 dBA or daily personal noise dose exceeding one hundred percent, or maximum sound pressure level exceeding 115 dBA at any time, or peak sound pressure level exceeding 140 dBC" [14].

2.4. Pure-Tone Audiometric Test

The audiometric data used in this study were originally collected as part of the workers' annual screening audiometric test, and were not intended for research purposes. The audiometric tests were conducted by certified Audiometric Testing Centers (ATC) using an audiometry booth calibrated to the standards set by the Department of Occupational Safety and Health. Workers were required to have a period of quiet for at least 14 h prior to testing. The tests used pure-tone air conduction at frequencies of 500, 1000, 2000, 3000, 4000 and 6000 Hz. The hearing threshold at 8000 Hz was not tested as it was not mandated by law [14].

Normal hearing is defined as air conduction hearing threshold levels of less than 25 dB at all test frequencies. Hearing loss is defined as air conduction hearing threshold levels of more than 25 dB at any test frequency. Hearing loss severity is categorized into mild (26 to 40 dB), moderate (41 to 70 dB), severe (71 to 90 dB) and profound (equal to or more than 91 dB) [25].

The data used in this study were limited to pure-tone air conduction audiograms only, which means that we were not able to confirm the diagnosis of sensorineural hearing loss for those with abnormal audiograms. Hence for the purpose of our investigation, we defined NIHL as bilateral high-frequency hearing loss (3000 Hz to 6000 Hz) with or without audiometric notch. Audiograms showing hearing loss only in the lower frequencies of 500 Hz to 2000 Hz were not considered as NIHL.

In practice, individuals with abnormal audiogram reports are required to undergo a repeat audiometric test within 3 months from the date of the previous audiometric test. Further examinations and investigations are to be arranged if indicated as such [25]. The results of the repeat audiometric test, however, are not part of this study.

2.5. Data Analysis

Data analysis was performed using SPSS Version 23. Statistical significance was set at $p < 0.05$. Categorical data were analyzed using Chi-square or Fisher's exact tests. Differences in the means of variables across three groups were calculated using one-way analysis of variance (ANOVA). Univariate and multivariate logistic regression were used to identify factors associated with NIHL.

3. Results

Our study subjects comprised 494 workers from nine different palm oil mills. Despite the differences in the plant layout for each mill, they generally share a similar processing workflow. The comparison of the noise risk assessment reports of the mills showed nine workstations commonly described as having excessive noise levels: grading area, loading ramp, sterilizer, press station, oil room, kernel station, boiler house, engine room and workshop. However, there were variations in the types of machineries used in each mill, and hence differences in the levels of noise exposure for individuals with similar work descriptions. The ranges of noise level for relevant workstations are summarized in Table 1.

Table 1. Range of noise levels at workstations in palm oil mills.

Workstation	Range of Noise Levels		
	$L_{EQ,8\ h}$ (dBA)	Max Level (dBA)	Peak Level (dBC)
Boiler house	84.4–96.1	106.2–122.3	124.2–143.0
Engine room	84.4–95.4	106.2–118.4	124.2–138.8
Grading area	76.5–81.6	102.7–109.4	116.6–128.2
Kernel station	87.1–93.0	98.6–117.5	122.1–140.7
Loading ramp	81.6–89.9	107.6–113.5	123.0–138.9
Oil room	84.5–90.8	95.1–120.3	120.3–138.4
Press station	85.1–90.5	94.2–122.5	125.1–138.8
Sterilizer	81.4–93.6	104.8–119.4	128.5–138.5
Workshop	77.8–91.7	101.3–121.3	128.6–145.2

Table 2 shows the overall characteristics of the study subjects. All but eight workers were males. Ages ranged from 21 to 59, with an average of 41 years old. The mean work duration was 15 years, with a minimum of 6 months. We categorized the workers into five different groups according to work descriptions: office workers, general workers, maintenance workers, operators, and supervisors. Office workers include managers, clerks, and laboratory staff. General workers include cleaners and landscape workers. Maintenance workers consisted of electricians and mechanics; this group of workers are stationed in the workshops, but also carry out maintenance duties in noisy processing stations within the mills. More than 60% of mill workers are operators who are positioned at various workstations along the processing line. Supervisors spend their working hours in office buildings, as well as in processing stations.

Based on the noise risk assessment reports, only 13% of workers were considered to be in the low exposure group. The moderate exposure group comprised 53.2% of all workers. These workers were either exposed to occasional noise, or were those whose workstation did not exceed the NEL. On an individual level, the daily noise exposure level for this group of workers would fall between 82 and 85 dBA. The high exposure group account for the remaining 33.8% of workers. These workers have been identified in the noise assessment reports to be exposed to hazardous level of noise exceeding the daily NEL of 85 dBA.

Overall, only 24.1% of workers had normal audiogram results for both ears, while 75.9% of them were shown to have some degree of hearing loss either unilaterally or bilaterally, including seven individuals with hearing loss only in the lower frequencies (500Hz to 2000Hz). However, from a total of 375 workers with hearing loss, only 251 fulfilled our operational definition of NIHL.

Table 2. Characteristics of study subjects (N = 494).

Variables	***n* (%)**
Gender	
Male	486 (98.4)
Female	8 (1.6)
Work description	
Office	64 (12.9)
General worker	17 (3.5)
Maintenance	101 (20.5)
Operator	301 (60.9)
Supervisor	11 (2.2)
Age (Range 21–59)	41.03 (10.095) [a]
20–29 years	80 (16.2)
30–39 years	147 (29.8)
40–49 years	126 (25.5)
50–59 years	141 (28.5)
Work duration (Range 0.5–39.4)	14.61 (10.29) [a]
≤5 years	109 (22.1)
6–10 years	123 (24.9)
11–15 years	52 (10.5)
16–20 years	50 (10.1)
>20 years	160 (32.4)
Exposure level	
Low	64 (13.0)
Moderate	263 (53.2)
High	167 (33.8)
Hearing condition (Worse ear)	
Normal hearing	119 (24.1)
Mild hearing loss	188 (38.0)
Moderate hearing loss	154 (31.6)
Severe hearing loss	29 (6.1)
Profound hearing loss	4 (0.2)

[a] Mean (SD).

Table 3 shows the characteristics of the study subjects according to the exposure levels. Mean age and work duration for all three exposure levels were compared using one-way analysis of variance (ANOVA), showing no significant difference between the groups.

Table 3. Characteristics of study subjects according to exposure level (N = 494).

Variables	**Exposure Level**			
	Low ***n* = 64**	**Moderate** ***n* = 263**	**High** ***n* = 167**	
Gender				
Male	57	262	167	
Female	7	1	0	
Work description				
Office	64	0	0	
General worker	0	17	0	
Maintenance	0	97	4	
Operator	0	138	163	
Supervisor	0	11	0	
		Mean (SD)		*p*
Age	41.95 (10.417)	41.77 (9.984)	39.53 (10.034)	0.059 [b]
Working duration	15.14 (10.647)	15.36 (10.428)	14.26 (9.910)	0.551 [b]

[b] One-way analysis of variance (ANOVA).

Table 4 summarizes the laterality and severity of high-frequency hearing loss among the workers. Bilateral hearing loss was detected in 251 out of 368 (68.2%) workers, while the remaining 117 (31.8%) had unilateral hearing loss. In terms of severity, most workers suffered from mild and moderate hearing loss, numbering 49.2% and 41.8%, respectively. The overall prevalence of NIHL among our study subjects was 50.8% (251 out of 494). Stratifying the prevalence according to exposure levels yielded values of 35.9% (23 out of 64) for low exposure, 51% (134 out of 263) for moderate exposure, and 56.3% (94 out of 167) for high exposure groups.

Table 4. High-frequency hearing loss laterality and severity according to exposure level (n = 368).

Variables	Exposure Level			Total, n (%)	p
	Low (n = 44)	Moderate (n = 195)	High (n = 129)		
Laterality					
Unilateral	21	61	35	117 (31.8)	<0.039 [c]
Bilateral	23	134	94	251 (68.2)	
Severity					
Mild	31	90	60	181 (49.2)	<0.034 [d]
Moderate	9	91	54	154 (41.8)	
Severe	2	13	14	29 (7.9)	
Profound	2	1	1	4 (1.1)	

[c] Chi-square. [d] Fisher's exact test.

Table 5 shows the factors associated with NIHL among the workers. Univariate logistic regression was used to test each of the variables; age, exposure level, and work duration. Table 6 shows the final model, which included only two factors: age and exposure level.

Table 5. Univariate logistic regression analysis of factors associated with noise-induced hearing loss (N = 494).

Variable	Crude OR (95% CI)	p
Exposure level		
Low	1	
Moderate	1.852 (1.052, 3.258)	0.033
High	2.295 (1.266, 4.162)	0.006
Age	1.088 (1.067, 1.110)	<0.001
Work duration	1.062 (1.043, 1.083)	<0.001

Table 6. Multivariate logistic regression analysis of factors associated with noise-induced hearing loss (N = 494).

Variable	B	Adjusted OR (95% CI)	p
Exposure			
Low		1	
Moderate	0.766	2.150 (1.159, 3.991)	0.015
High	1.242	3.462 (1.784, 6.716)	<0.001
Age	0.091	1.095 (1.072, 1.118)	<0.001

Constant = −4.518; forward likelihood ratio method was applied; no multicollinearity and no interaction; Hosmer Lemeshow test, p = 0.53; classification table 69% correctly classified; area under ROC curve = 75%.

4. Discussion

Our data show an overall NIHL prevalence of 50.8% in a sample consisting of only 33.8% workers exposed to daily noise level exceeding the NEL. In a small study among palm oil mill workers in the neighboring country of Indonesia, the prevalence was lower, at 35%, despite their having more than 75% of workers exposed to daily noise level exceeding 85 dBA [12]. Another study involving a similar population reported a much higher prevalence of 89.3%. However, all participants in that particular study were exposed to hazardous daily noise levels [10]. Both studies defined NIHL using the average hearing threshold at frequencies of 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz. A local study among manufacturing workers exposed to noise exceeding the NEL reported a prevalence of 73.3% [17]. As a comparison, the prevalence among our high exposure group was lower, at 56.3%. The operational definition of NIHL, however, was different compared to our study—air conduction hearing threshold exceeding 25 dB at any frequency, including those with unilateral hearing loss. This may have contributed to a higher prevalence, since more workers would be considered to have NIHL. A more comparable definition of NIHL was used in a study among vector control workers in Malaysia [26]. The authors defined NIHL based on occupational exposure, presence of audiometric notching at 4000 Hz, and bilateral involvement. The prevalence of NIHL was relatively low, at 26.5%. Studies conducted among factory workers in Myanmar and China also reported low prevalences of 25.7% and 28.8%, respectively [16,24]. The participants in these two studies consisted of both low and high noise-exposure groups, comparable to our study participants. It must be noted that a direct comparison of prevalence between various studies is almost impossible due to the dissimilarities in the definition of NIHL, as well as the inclusion criteria for study subjects.

Our operational definition of NIHL is bilateral high-frequency hearing loss with or without audiometric notch. In clinical practice, occupational NIHL is typically characterized as bilateral sensorineural hearing loss, affecting the hearing threshold at 3000 Hz and higher, with the presence of an audiometric notch [27,28]. However, confirmatory audiometric tests, including air and bone conduction, are still necessary in order to confirm such diagnoses, especially in cases where asymmetrical hearing loss is detected [29]. Unilateral hearing loss due to noise exposure is known to occur in situations where the exposure is asymmetrical, for example gunshot noise for firearm handlers or wind noise for drivers [27,28]. In our study population, asymmetrical exposure can occur if personal protective devices are not worn properly, either intentionally or unintentionally. Nevertheless, unilateral hearing loss is more commonly associated with retrocochlear lesions, such as acoustic neuroma, instead of NIHL [28].

NIHL can affect both low and high frequencies. However, the effects on lower frequencies are less common, except in cases with extensive exposure to hazardous noise [28]. High-frequency notch is a typical finding in the audiograms of noise-exposed individuals, although it is not pathognomonic of NIHL [29]. It is worth noting that the definitions of "notch" vary, as described in numerous studies [30,31]. We believe that the lack of a standardized definition of audiometric notch may pose an issue in its application as a criterion for diagnosing NIHL, particularly when using data from screening audiograms alone. In addition, our study participants' hearing threshold levels at 8000 Hz were not tested. This mean that we could not elicit the classical audiogram pattern of recovery at 8000 Hz [27]. More importantly, the notch becomes less apparent in older individuals [28]. Thus, we did not include audiometric notch as a requirement to define NIHL. However, we acknowledge the importance of the audiometric notch as supporting evidence to establish the diagnosis of NIHL in clinical practice, especially in cases where workers are found to have sensorineural hearing loss. Hence, a hearing threshold level of 8000 Hz should be included in the screening audiometric tests for noise-exposed workers.

The findings in this study must be interpreted with caution, mainly due to the fact that we only analyzed data from screening audiometric procedures, as opposed to actual confirmatory audiometric tests. The prevalence that we calculated may have been an underestimation, since we did not include cases with unilateral hearing loss. Conversely, the results of air conduction screening audiometry may produce false positives, leading to an overestimation of prevalence. This is particularly true in cases where the hearing losses detected were actually conductive in nature, or were due to pathological conditions other than cochlear hair cell damage. Given the limitations in our data, we believe that our operational definition of NIHL is a reasonable arrangement to estimate the magnitude of the disease in the study population.

The daily noise exposure level of 85 dBA is widely accepted as the permissible exposure limit in many countries around the world [5,32,33]. Numerous studies have shown that exposure to noise beyond this limit increases the risk of developing NIHL [21,34]. However, some research has suggested that hearing loss can also occur upon exposure to noise between 80 and 85 dBA [27,33,35]. In our study, exposure to noise levels between 82 and 85 dBA was considered as moderate exposure, in relation to the term "excessive noise" introduced in the new Malaysian noise regulation [14]. Interestingly, our data demonstrate the significant effects of both moderate and high exposure levels on the outcome of NIHL. Workers categorized in the moderate exposure group are, by definition, not exposed to daily noise level exceeding the permissible limit, and thus are not required to undergo annual audiometric tests. In practice, this can lead to a significant level of undiagnosed NIHL in the study population. Our findings show that this group of workers actually had more than two times the odds of having NIHL compared to those in the low exposure group when adjusted for age. We acknowledge that this could have been the result of misclassification bias, particularly involving workers who may have been assigned to different workstations throughout their employment. Another possible explanation for this is that we did not measure other confounders, such as smoking, impulse noise, recreational noise exposure, and compliance to hearing protection devices [21,36].

Bivariate logistic regression showed that exposure level, age, and work duration are all significant factors associated with NIHL. However, multivariate logistic regression produced a final model consisting of only exposure level and age. A probable explanation for the inclusion of age and the exclusion of working duration is that these factors are both temporal factors, and thus would be highly correlated. Our findings are comparable with the results documented in several other studies. In Tanzania, the prevalence of NIHL among metal workers was found to be associated with older age groups and noise exposure [15]. In a study conducted among vector control workers in Malaysia, participants were split into two age groups: <40 and ≥ 40 years old. It was shown that age group and noise exposure were significant predictors of NIHL [26]. In Myanmar, NIHL was more prevalent among textile workers aged 35 and older, as well as those with tinnitus. Other factors such as noise exposure, work duration, and smoking were not significant predictors of NIHL [16]. A large retrospective study among mining and oil and gas extraction workers in America also demonstrated results in line with our findings—NIHL was significantly associated with high noise levels and older age groups [37].

Pertaining to the protection of the hearing health of workers in the palm oil manufacturing industry, engineering and administrative control measures alone may not be sufficient. Our data show that a significant proportion of workers stationed along the processing line are still exposed to hazardous levels of noise, and thus would need to be equipped with hearing protection devices. According to the law, employers are responsible for providing education and training regarding noise exposure for workers who are exposed to excessive noise at the workplace, at least once a year. Employers are also required to provide these workers with suitable, efficient and properly maintained hearing protection devices [14]. Although we did not explore the workers' compliance to hearing protection devices, this may have been a contributing factor to the high prevalence of NIHL. A local study conducted among manufacturing workers reported a low compliance rate of less than 40% [38]. In a qualitative study conducted among noise-exposed sawmill workers, it was shown that the workers did not comply to the use of hearing protection devices due to three main factors: comfortability, lack of awareness, and prevention of communication [39]. Hence, there is a crucial need for employers to evaluate the implementation of hearing conservation programs in the workplace to ensure that workers in the high-risk group are adequately protected from occupational noise hazards.

The strength of our study lies in the use of data from industrial noise risk assessments and workers' audiometric screening tests. These are actual data, which would be used to manage noise hazards and guide the implementation of hearing conservation programs at oil mills. Obtaining data from employers also enabled us to get a relatively bigger sample, encompassing all workers with varying levels of noise exposure. This is particularly beneficial in enabling comparisons across different exposure groups.

Since this study was limited to secondary data, we did not manage to include other possible predictors of NIHL in our data analysis. It was also not possible to confirm the diagnosis of NIHL for workers with abnormal audiogram reports.

Overall, the findings in this study outline the need for a precautionary approach when managing the risk of occupational NIHL in the palm oil industry. Occupational doctors and industrial hygienists must consider the risks of workers developing NIHL, despite not being identified as high-risk according to their workplace noise evaluation. We propose that further research should be undertaken related to the risk of developing NIHL in those exposed to excessive noise below the permissible limit, in order to confirm our findings.

5. Conclusions

This study highlights the need for a precautionary approach to better protect palm oil mill workers from workplace noise hazards. Risk stratification based entirely on workplace noise risk assessment reports may lead to inaccurate evaluations and result in the suboptimal implementation of hearing conservation programs. The effectiveness of occupational noise hazard control at all levels must be evaluated to ensure the preservation and improvement of the hearing health of vulnerable group of workers.

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Review

Quantities and Units in Chemical and Environmental Engineering

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Abstract: The International System of Quantities (ISQ) shall be used in education and textbooks, in scientific and engineering journals, in conference papers and proceedings, in industry, among others. The names of quantities together with their symbols and units are being published by the International Organization for Standardization, the standard ISO 80000 Quantities and units, composed of 13 parts. Mathematics and natural sciences (physics, light and radiation, acoustics, physical chemistry, atomic and nuclear physics, condensed matter physics) compose most of the parts. In addition, some engineering disciplines (mechanics, thermodynamics, electromagnetism) and characteristic numbers are covered. The units are based on the International System of Units (SI). Unfortunately, chemical and process engineering, as well as environmental engineering and engineering economics, are not dealt with in the standard. In this paper, they are proposed as an additional part of the ISO standard with a tentative name Chemical and environmental engineering. The additional part of the standard is suggested to include (a) reaction and separation engineering together with mass transfer and reaction kinetics, (b) process design, control, and optimization, (c) process economics, mathematical modeling, operational research, and (d) environmental engineering with climate change, pollution abatement, an increase in resource efficiency, zero waste and circular economy. The number of quantities is planned but not limited to about 70, the average of ISO 80000 parts. Each quantity item contains a quantity name and definition (including an equation if suitable), SI unit, and remarks (running number will be added later). The rules are defined in ISO 80000-1 General rules, and the practice of the other ISO 80000 parts is respected; the quantities already included in the other parts are not repeated. In addition, the IUPAC (International Union of Pure and Applied Chemistry) Green Book rules are respected. The literature used included traditional textbooks, encyclopedias, handbooks from the chemical engineering and environmental fields. Some common mistakes in printing symbols of quantities and units are mentioned.

Keywords: chemical; environmental; engineering; quantities; standard; symbols; units

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1. Introduction

After the letters, numbers, and units, the system of quantities was the last one developed and standardized globally. Quantity is a property of a phenomenon, body, or substance, where the property has a magnitude that can be expressed by means of a number and a reference (unit). The first international organizations trying to standardize chemical and physical quantities have been the International Union of Pure and Applied Physics, IUPAP (established in 1922), and the International Union of Pure and Applied Chemistry, IUPAC (formed in 1919). IUPAP prepared its first edition of Symbols, Units and Nomenclature in Physics in 1961 for official use only; its 1987 revision is available online [1]. IUPAC published the first edition of the Manual of Symbols and Terminology for Physicochemical Quantities and Units in 1969 [2]. After the 3rd edition, they changed the title of the manual and published it as a Green Book, again with three editions [3]. The Green Book is available on Internet, too.

In 1988, the International Organization for Standardization, ISO, in cooperation with International Electrotechnical Commission, IEC, published the first edition of international standard ISO 31 Quantities and units in 13 parts [4], and ISO 1000 SI units and recommendations for use [5]. In 1992 a new version of both standards was published. In 2009, the two standards were substituted by ISO 80000 Quantities and units containing 13 somewhat reorganized parts [6]; the last edition was published in 2019, the exception being the parts mentioned in parentheses (the parts 1 and 6 are planned to be updated in the year 2021):

(1) General (2009)
(2) Mathematics
(3) Space and time
(4) Mechanics
(5) Thermodynamics
(6) Electromagnetism (2008)
(7) Light and radiation
(8) Acoustics (2020)
(9) Physical chemistry and molecular physics
(10) Atomic and nuclear physics
(11) Characteristic numbers
(12) Condensed matter physics
(13) Information science and technology (2008)

The general part contains information about quantities and units, printing rules, rules for terms in names for physical quantities, rounding of numbers, and logarithmic quantities. In parts 3–13 (part 14 has been withdrawn), the quantities of each subset are listed, including item number, quantity name, symbol and definition, unit symbol, and eventual remarks. Since 2019, each part has an alphabetical index of quantities at the end to enable searching for the items. Three further parts, 15–17 (Logarithmic and related quantities, Printing and writing rules, Time dependency), are under development [7].

As can be seen from the above-cited list of ISO 80000 parts, chemical and process industries (CPI) are not included, although they are very important in many respects (turnover, profit, investments, employment, research, etc.). Besides the chemical industry, CPI involves pharmaceutical, cellulose and paper, metal, ceramic, textile, food and beverage, and other industries. The area includes process, plant, and equipment modeling, design, construction, analysis, optimization, operation, control, process economics, safety, hazard assessment, transport phenomena, etc.

There is also no standard on quantities in environmental science and engineering, although we are in the climate change/crisis, facing species extinction, pollution, and raw-materials scarcity. Even quantities in the ISO 14000 family on environmental management, e.g., the performance indicators in ISO 14031 standard, are not obeying the ISO 80000 and SI rules [8]. The Paris agreement, European Green Deal, Net-zero emissions by 2050, sustainable development goals are some of the most frequent buzzwords that we are facing every day. They are dealing with greenhouse gas emissions, renewable sources, critical raw materials, biodiversity, resource efficiency, zero waste, circular economy, etc. Therefore, it is necessary to define internationally agreed names, symbols, and units for the quantities used in the area.

2. Methods

The literature search included chemical and environmental engineering textbooks, manuals, standards, lexicons, encyclopedias, and handbooks, e.g., Ullmann's Encyclopaedia [9], Perry's Chemical Engineers' Handbook [10], SI brochure [11], and Google searches. As the number of items is limited, the most important quantities have been selected according to the importance and frequency of their usage using the cited references and personal experience.

The proposal starts with chemical engineering quantities, continues with process economic ones in design, and finishes with the environmental ones. Some common mistakes in symbols of quantities and units are mentioned. They can also be found in the literature [12].

The proposed terms will be discussed at some professional meetings and published in this journal. After improvements, they will be sent to the EFCE (European Federation of Chemical Engineering), the AIChE (American Institute of Chemical Engineers), the IChemE (British Institution of Chemical Engineers), and the DECHEMA (Deutsche Gesellschaft für chemisches Apparatewesen). After their approval, they will be asked to send the proposal to the Technical Committee ISO/TC 12 Quantities and units.

3. Results and Discussion

Chemical and process engineering quantities are very exhaustive as they cover many topics based on chemistry, physics, mathematics, economics, etc. that deal with a very broad range of materials, methods, and equipment, e.g., ([9,10]):

- Principles of fluid and particle dynamics, heat and mass transfer, chemical thermodynamics and kinetics, statistics, and optimization methods;
- Very diverse reactions: homogeneous liquid or gas ones, gas-liquid, or gas-liquid-solid ones, using blast, or rotary furnaces, fixed or fluidized beds, heterogeneous gas catalysis, electrolysis, photo-, or plasma-chemistry, etc.;
- Unit operations such as size reduction and classification, transportation, and storage, mechanical, magnetic, electric separations, mixing and conveying, heating, cooling, adsorption, absorption, extraction, ion exchange, distillation, evaporation, sublimation, refrigeration, crystallization, and drying;
- Process design, construction, operation, control, and development with modeling, costing, simulation, optimization, process safety, pollution, energy integration, waste management, and reuse, circular economy, renewable energy.

Therefore, an ISO standard about quantities and units in these fields is truly needed. Besides it, some additional chapters in the IUPAC Green Book [3] would also be welcome.

3.1. Basic Chemical Engineering Principles and Unit Operations

Some basic quantities that are not included in other parts of ISO 80000 are presented in Table 1. Values of constants are taken from the SI brochure [11] and CODATA [13].

Table 1. Basic chemical engineering quantities.

Name	Symbol	Definition	Unit	Remarks
Avogadro constant	N_A, L	$N_A = N/n$	mol^{-1}	$6.022\,141\,76 \times 10^{23}$
Boltzmann constant	k, k_B		$J\ K^{-1}$	$1.380\,649 \times 10^{-23}$
Faraday constant	F	$F = eN_A$	$C\ mol^{-1}$	$9.648\,533\,212 \times 10^{4}$
Henry's law constant	k_H	$k_{H,B} = (\delta f_B/\delta x_B)_{xB\,=\,0}$	Pa	
Planck constant	h	$h = E/f$	J s	$6.626\,070\,15 \times 10^{-34}$
Stefan-Boltzmann constant	σ	$M_e = \sigma T^4$	$W\ m^2\ K^{-4}$	$5.670\,374\,419 \times 10^{-8}$
2nd virial coefficient 3rd virial coefficient	B C	$pV_m = RT\,(1 + B/V_m + C/V_m{}^2 + \ldots)$	$m^3\ mol^{-1}$ $m^6\ mol^{-2}$	$pV_m = RT\,(1 + B_p\,p + C_p\,p^2 + \ldots)$
Coefficient of mass transfer	k_c	$k_c = j_n/\Delta c_A$	$m\ s^{-1}$	
Specific surface area	s	$S = A/m$	$m^2\ kg^{-1}$	
Logarithmic-mean temperature difference	ΔT_{lm}	$\Delta T_{lm} = (\Delta T_2 - \Delta T_1)/\ln(\Delta T_2/\Delta T_1)$	K	LMTD

Symbols—name, unit: A—area, m^2; c—concentration, mol/m^3: e—proton charge, C, f—fugacity: Pa, j_n—amount(-of-substance) flow, $mol/(m^2\ s)$; M_e—radiant exitance $W\ m^{-2}$, N—number of entities, 1; n—amount(-of-substance), mol; p—pressure, Pa; R—molar gas constant; J/(mol K); T—thermodynamic temperature, K; V_m—molar volume, m^3/mol; x—amount(-of-substance) fraction, 1.

3.2. Chemical Reaction Engineering

Chemical reaction is the heart of chemical engineering activity—reactants are flowing into a reactor where they react, and products flow out of the reactor. Therefore, amount flow rates must be discussed first. The symbol F is used in English literature [14], $\dot{n}$ Chemical Reaction Engineering in German one [15]. Mass flow rate, q_m (kg/s), and volume flow rate, q_V (m^3/s), are defined in ISO 80000-4-30.2 and 4-31, but amount-of-substance (shorter "amount" with the unit mol) flow rate is not; it is not defined in the Green Book [3], either. By analogy, $\mathrm{q_n}$ (mol/s) could be used (Table 2). ISO 80000-4 defined mass flow, $\boldsymbol{j}_\mathrm{m}$, too; therefore, amount flow, $\boldsymbol{j}_n$, is also included in the list.

Table 2. Chemical reaction engineering quantities.

Name	Symbol	Definition	Unit	Remarks
Amount flow	$\boldsymbol{j}_n$	$\boldsymbol{j}_n = c\boldsymbol{v}$	mol m^{-2} s^{-1}	
Amount flow rate	q_n	$q_n = \int\int \boldsymbol{j}_n {\cdot} \boldsymbol{e}_n\, dA$	mol s^{-1}	$\boldsymbol{e}_n$—normal vector
(Fractional) conversion	X_B	$X_\mathrm{B} = (n_\mathrm{B} - n_\mathrm{B0})/n_\mathrm{B0} = 1 - c_\mathrm{B}/c_\mathrm{B0}$	1	$\mathrm{d}X_\mathrm{B} = \mathrm{d}c_\mathrm{B}/c_\mathrm{B0}$
Selectivity	σ_P	$\sigma_\mathrm{P} = dc_\mathrm{P}/(dc_\mathrm{P} + dc_\mathrm{S})$	1	
-(Fractional) yield	φ Φ	$\varphi = \mathrm{d}c_\mathrm{P}/(-\mathrm{d}c_\mathrm{A})$ $\Phi = c_\mathrm{Pf}/(c_\mathrm{A0} - c_\mathrm{Af})$	1 1	Instantaneous Overall, f—final
Rate of conversion	ω	$\omega = \mathrm{d}\xi/\mathrm{d}t$	mol s^{-1}	
Specific rate of conversion	r_m	$r_m = (1/m)\,(\mathrm{d}n_i/\mathrm{d}t)$	mol kg^{-1} s^{-1}	
Areic rate of conv.	r_A	$r_A = (1/A)\,(\mathrm{d}n_i/\mathrm{d}t)$	mol m^{-2} s^{-1}	
Volumic rate of conversion	r_V	$r_V = (1/V)\,(\mathrm{d}n_i/\mathrm{d}t)$	mol m^{-3} s^{-1}	V—reactor volume
Rate of reaction	r_c $\mathrm{r_P}$	$r_c = (1/\nu_\mathrm{P})\,(\mathrm{d}c_i/\mathrm{d}t)$ $\mathrm{r_P = (1/RT)\,(dp_i/dt)}$	mol m^{-3} s^{-1} mol m^{-3} s^{-1}	For liquids For ideal gases
Rate constant	k	$r = k\Pi_\mathrm{B}{c_\mathrm{B}}^{m\mathrm{B}}$	$(\mathrm{m}^3/\mathrm{mol})^{\mathrm{m}-1}$ s^{-1}	m—order of reaction
Residence time distribution, RTD	$\boldsymbol{E}$	$\int_0^\infty \boldsymbol{E}\, dt = 1$	1	Age distribution at reactor exit
Space-time	τ	$\tau = V_r/q_{V,F}$	s	F—feed
Pace-velocity	s	$s = 1/\tau$	s^{-1}	
Recycle ratio	R	$R = q_{V,\mathrm{r}}/q_{V,\mathrm{f}}$	1	r—recycled, f—final

Symbols—name, unit: A—area, m^2; c—concentration, mol/m^3; n—amount (-of-substance), mol; p—pressure, Pa; t—time, s; v—velocity, m/s; ν—stoichiometric number, 1.

Conversion is the next quantity to be defined. It is often called fractional conversion (Umsatzgrad). The ISO 80000-9 and the Green Book cite extent of reaction, ξ (mol), and the Green Book also rate of (absolute) conversion, $\dot{\xi} = \mathrm{d}\xi/\mathrm{d}t$ (mol/s). In American textbooks, the symbols X_A, or x_A, or f_A are used for conversion of a reactant A, while U_A (Umsatz) is used in German ones. X_A is adopted here. Subscripts A, B, C, etc., are used for reactants, and P, R, S, etc., for reaction products. Selectivity, σ_P is the amount ratio of desired product P to all products S formed. The definition in Table 2 is appropriate for reactors with constant volume. For selectivity calculation of a batch reactor, amounts of product P and reactant A are used $\sigma_\mathrm{P} = n_\mathrm{P}/(n_\mathrm{A0} - n_\mathrm{A})$. For continuous reactors amount flows are needed, $\sigma_\mathrm{P} = q_{n,\mathrm{P}}/(q_{n,\mathrm{A0}} - q_{n,\mathrm{A}})$. Yield (Ausbeute) is the amount ratio of desired product P to reactant A fed. It can be instantaneous, φ, or overall, ϕ. Yield is always the selectivity times the conversion, $\varphi_\mathrm{P} = \sigma_\mathrm{P} X_\mathrm{A}$.

The name "rate of reaction" shall be used with constant volume fluids or with ideal gases only. In other cases, the rate of conversion for any species i is proposed to be used; the "specific rate of conversion" is applied in cases of solid in fluid-solid systems. The "areic rate of conversion" is suitable for interfacial surfaces in two-fluid systems and in the surface of solid catalysts in gas-solid systems. The "volumic rate of conversion" is based on the volume of a reactor, not the volume of a fluid; it could also be named "rate of production", but this name is used in the case of selectivity, $q_{n,\mathrm{B}} = \phi\, q_{n,\mathrm{A0}} = \sigma_\mathrm{B} X_\mathrm{A}\, q_{n,\mathrm{A0}}$.

Equilibrium constants are described in ISO 80000-9; space-time, space velocity, and yield are not. Space-time, τ (s), is the time required to fill a reactor volume with its volume flow rate of feed at specified conditions. Space velocity, s (s^{-1}), is the space-time reciprocal. Recycle ratio, R (1), is the quotient of the volume flow rate returned to the reactor entrance and the one leaving the system.

Only a few quantities from reaction engineering are presented in Table 1. Single and multiple (series or parallel) reactions, elementary and nonelementary are known, and the number of molecules (molecularity with different orders of reaction) can differ and influence the rate equation. Temperature and pressure effects can vary, and the reaction can be exothermal or endothermal. In addition, we know different types of reactors—batch, plug flow, mixed flow, recycle ones. Flow patterns and contacting can be ideal or non-ideal; in the last case, dispersion, convection, or earliness of mixing must be accounted for. Finally, fluid-fluid (liquid or gas), fluid-solid, catalytic, and various biochemical (enzyme or microbial) reactors exist—heat and mass transfer become important in these cases, too. It will be difficult to standardize all of the quantities used in one standard. Especially so because process control, economics, and optimization influence the design of reactors.

Regarding axial dispersion, the dispersion coefficient, D (m^2/s), mean time of a passage, $\bar{t}$ (s), and variance, σ^2, are important quantities; the probability distribution, statistics, and uncertainties are described in the Green Book [3] (pp. 151, 152). In the case of catalytic systems, the rate of conversion equations from Table 2 can be used; they can be based on the volume of voids in the reactor, mass or volume of catalyst pellets, catalyst surface area, or total reactor volume; activity of a catalyst, a (1), may also be important. For heterogeneous reactions with two or more phases, the standard could contain some other quantities such as interfacial area density, a (m^2/m^3), effectiveness factor (ε or η, 1), mass transfer coefficient of the gas film, β, or k_g, or liquid film, k_l (m/s), Henry's constant, H (Pa m^3 mol^{-1}), Thiele modulus, M_T (also h_T, or ϕ in German literature), Wagner or Weisz modulus, M_W, and Hatta modulus, M_H (the unit 1 for all of them).

3.3. Other Unit Operations

Unit operations are numerous and differ very much from one another. Let us take distillation as an example. It is normal to write amount flow rates (mol/s) with a symbol of a flow rate name—F for feed flow rate, D for distillate flow rate, S for side-stream flow rate, V for vapor flow rate, etc. Correctly, q_n could be used as a quantity symbol with a subscript denoting different flow rates, $q_{n,\mathrm{F}}$, $q_{n,\mathrm{D}}$, $q_{n,\mathrm{S}}$, and $q_{n,\mathrm{V}}$ in this case. The second disrespect of ISO 80000 rules is the name "duty" for the heat flow rate (W), e.g., condenser duty, reboiler duty, while their symbol, $\dot{Q}$ is in accordance with the ISO one. In addition, void fraction or even "voidage", ε is not well defined—volume fraction of voids is the right name, and φ the right symbol. Some other proposals for quantities of unit operations and their symbols are presented in Table 3.

Table 3. Quantity names, symbols, and units in separation units.

Name	Symbol	Definition	Unit	Remarks
Amount flow	j_n	$j_n = q_n/A$	mol m^{-2} s^{-1}	
External reflux ratio	R	$R = q_{n,\,N+1}/q_D$	1	$q_{N+1}/V_N = R/(1+R)$
Vapor-liquid equilibrium ratio	K_i	$K_i = x_i/y_i$	1	
Relative volatility	α_{ij}	$\alpha_{ij} = K_i/K_j$	1	
Fugacity coefficient	ϕ_i	$\phi_i = f_i/p$	1	$\phi_i = 1$ for ideal gas
Volume fraction of voids	φ_v	$\varphi_v = V_v/V_{tot}$	1	

Table 3. *Cont.*

Name	Symbol	Definition	Unit	Remarks
Efficiency of batch experiment	η_b	$\eta_b = 1 - e^{-ktb}$	1	t_b—batch mixing time
Efficiency of a continuous process	η_c	$\eta_c = k\theta/(1 + k\theta)$	1	θ—total liquid residence time

3.4. Process Development and Design

Process development data, which can be internal or external, process evaluation that includes capacity determination, and economics, process optimization, and decision making, are important. Table 4 presents the most frequent quantities in process engineering optimization, using mathematics and economics. Statistics is well covered in ISO standards; therefore, it will not be regarded here. Economics, on the other side, is not standardized, and often acronyms are used instead of symbols; it also lacks international coordination [16].

Table 4. Chemical and process engineering design economics.

Name	Symbol	Definition	Unit	Remarks
Cost	C		EUR, USD, ...	Cost index
Investment	I		€, $, ...	Fixed capital
Interest rate	i		%	V_p—present value
Future value	V_f	$V_f = V_p\ (1 + i)^N$	1 (% = 10^{-2})	N—number of years
Revenue, net sales	R, S_n	$S_n = S_g - O_s$	€, $, ...	S_g—gross sales
Turnover ratio Capital ratio	r_{to} r_c	$r_{to} = S_g/I$ $r_c = I/S_g$	1 1	Reciprocals
Production rate	q_m	$q_m = m/t$	kg/s, t/a	Capacity dependent
Operating expenses	O	$O = O_d + O_i$	€, $, ...	Direct + indirect expe.
Depreciation	D	$D = I/N$	€/a, $/a, ...	With no salvage value
Gross income	P_g	$P_g = R - O - D$	€/a, $/a, ...	Gross profit
Net income	P_n	$P_n = Pg\ (1 - \tau)$	€/a, $/a, ...	Net profit, τ—tax rate
Income tax	T	$T = \tau\ (R - O - D)$	%	
Net profit after tax	P_n	$P_n = Pg\ (1 - \tau)$	€/a, $/a, ...	Net income
Cash flow rate	q_c	$q_c = P_n + D$	€/a, $/a, ...	
Return on investment	R_{oi}	$R_{oi} = P/I \times 100$	%	Internal rate of return
Payout time	t_{po}	$t_{po} = I/P_n$	a	Payout period, years

The most used cost indices are Marshall and Swift (M&S, since 1926), Chemical Engineering (CE, since 1958), and Nelson-Farrar (since 1946) ones. Capital investment includes equipment cost, instrumentation, piping, insulation, electrical, and engineering costs without any contingency; contingency is about 15%–20% of capital investment—when added to capital investment, the battery-limits capital investment is obtained. Working capital includes the fund for wages and salaries, purchase of raw materials, supplies, etc.

Operating expense is the sum of expenses for the processing of a product plus general, administrative, and selling expenses. They can be grouped into direct, indirect, and product expenses; direct expenses are raw materials, utilities, labor, maintenance, supervision, payroll charges, operating supplies, clothing and laundry, technical service, royalties, and environmental control. Indirect expenses include depreciation and plant indirect costs. Total manufacturing expense is adding packaging, loading, and shipping expenses to the operating expense. Revenues are the net sales received from selling a product to a customer. The value added to the product is the difference between the raw material expenses and the selling price of that product.

The time value of money is diminishing because of inflation. Interest rate includes the expectation that the borrowed capital should earn. The present value of money, V_p, is lower than the future value, V_f. When a company loans money, a charge is made for the use of borrowed funds—the interest rate includes inflation expectation, the borrower's cost, and his desired profit. The cost of capital is what it costs the company to borrow money from all sources (loans, bonds, stocks); it is expressed as an interest rate.

Besides the term depreciation, quantity amortization is often used—there is a slight difference between them. If the period of life is known exactly, the annual expense is called amortization. If this time is estimated, it is called depreciation.

The rate of return and its variations are known by various names, e.g., internal rate of return, the interest rate of return, discounted cash flow rate of return.

3.5. Environmental Quantities, Units, and Symbols

Sustainable development with its three pillars (environmental, societal, economic ones) is gaining importance, and so is the Paris agreement with the 17 sustainable development goals (SDGs). The most problematic is the climate crisis caused by greenhouse gas (GHG) emissions with global warming. Table 5 presents some of the most important quantities in this area, starting with GHG emissions and climate change and ending with pollution.

Table 5. Environmental quantities with symbols and units.

Name	Symbol	Definition	Unit	Remarks
Amount fraction of CO_2 equivalent	$x(CO_{2,eq})$	$x_B = n_B / \sum_i ni$	μmol/mol	In atmosphere
Emissions coefficient of electricity	$E_e(CO_{2,eq})$	$E_e = m/W$	kg/(kW h)	Not factor
Emission coefficient of travel	E_l	$E_l = m/l$	g/km	Various forms
Carbon footprint per user	F_c	$F_c = m/t$	t/a	Per person, . . .
Ecological footprint	F_e	$F_e = A_{eq}$	ha	
Water footprint	F_w	$F_w = V/t$	m^3/a	
Amount fraction of air pollution	$x(SO_2)$	$x = n_{SO2}/\Sigma n$	nmol/mol	
Mass concentration of particulate matter pollutants, $d \leq (2.5, 10)$ μm	$\gamma_{PM2.5}$ γ_{PM10}	$\gamma = m_{PM}/V$	$\mu g/m^3$	In air
Number concentration, e.g., microplastics	C	$C = N/V$	m^{-3}	In lake, ocean
Mass concentration, heavy metal	$\gamma(Hg)$	$\gamma = m_{Hg}/V$	μg/L	In water
Mass fraction, heavy metal	$w(Pb)$	$w = m_{Pb}/\Sigma m$	mg/kg	In soil
Waste generation per capita	q_m	$q_m = m/t$	kg/a	Mass flow rate
Mass fraction of waste recycled	w_r	$w_r = m_r/m_w$	1, %	Not recycling rate

GHGs contain, besides the water vapor, H_2O, the most dangerous gases: carbon dioxide, CO_2, methane, CH_4, nitrous oxide, N_2O, ozone, O_3, chlorofluorocarbons, CFCs, and hydrofluorocarbons, HFCs; they are recalculated into CO_2 equivalents. The emissions coefficient of electricity is also named "electricity-specific emission factor", but the term "factor" should be used when the two quantities (mass and electricity in our case) have the same dimension, its unit is 1; the term "coefficient" shall be used when the two quantities have different dimensions. In ecological footprint, the unit global hectare, with the symbol gha, is used; it is wrong—the area taken into account is global, but the unit is hectare—global area, A_g, in ha [17]. The literature is usually writing about their concentrations or amount/volume fractions in ppm (parts per million) as a unit. The quantity is not concentration (mol/m^3) but rather amount fraction (μmol/mol). The units, ppm, ppb (part per billion), etc., are not recommended by IUPAC; therefore, amount (of substance) fraction with the symbol x and unit μmol/mol, or nmol/mol, respectively, are used.

GHGs originate from the burning of fossil fuels in transportation, energy production, industry, residential areas, fermentation of waste, and agriculture. The $CO_{2,\,eq}$ emissions can be expressed in different ways, e.g., as mass per energy produced (kg/(kW h), or mg/J), mass per volume of fuel (mg/L), mass per distance traveled (g/km), mass of CH_4 per agricultural area released or absorbed (kg/ha). They can be calculated per person, per company, per city, per country, or per world. No special names and symbols are available now. Many mistakes can be observed in statistical collections and in literature, e.g., by including the CO_2 formula or the words "per person" or "per capita" into the units.

In Table 5, some tentative symbols for quantities and units regarding emissions are proposed by respecting the ISO 80000 rules. Using the proposed names, symbols, and units, different forms of traveling (car, train, plane, etc.) or different users of carbon footprint can be addressed and compared. Many other footprints have been developed (water, land, nitrogen, phosphorus, material, biodiversity, chemical, plastic, energy, etc.); the environmental footprint family, relating to the nine planetary boundaries and their connection with SDGs, is being developed [18].

Pollution of air, water, and soil with chemical substances, heavy metals, particulate matter, noise, electromagnetic radiations, etc., is the second major environmental problem of modern society. Accepted terminology and symbols can be used for them, but they are usually not applied. An international standard could improve their usage. Waste minimization, recycling, and circular economy are becoming more and more important. "Waste generation" (per capita) actually means an abbreviated name for "mass flow rate of waste generated". "Recycling rate" means mass flow rate of recycled material (q_m, kg/a) that is a different quantity; therefore, the name is substituted by the "recycling fraction" in %.

4. Conclusions

Chemical and process engineering, as well as environmental science and engineering, are not represented in the 13 parts of ISO 80000 standard on quantities and units. The chemical industry alone sales in 2019 (3.66 TEUR—trillion euros, 10^{12} EUR) reach 4.2% of the world's GDP (gross domestic product, 74.76 TEUR). It is very interdisciplinary and specialized and different from the manufacturing industry. It is also very important in the area of sustainable engineering, especially in environmental sustainability. Therefore, it deserves a special part in the standardization of quantities and units. The literature review has shown that there are many names of quantities and units that are not in accordance with the ISO 80000 rules. Even worse is the situation with quantity symbols and units—many symbols of quantities are not coherent with the international system ISQ, and many units do not respect the SI rules. Acronyms cannot be used as quantity symbols, and SI units may not be intermixed with quantity specifications.

This paper tried to discuss and propose some of the most important quantities in the areas of chemical and environmental engineering and process economics. Regarding the names and symbols selected, the rules accepted in the systems of ISQ and SI were tried to be obeyed. The choice of quantities is, of course, just an illustration of names and symbols to be included in the proposal. Health and safety, statistics, management, and quality were not discussed as standards for them exist, but this does not mean that a review of quantity names, units, and symbols in those areas is not needed. In addition, basic concepts of process modeling, simulation, synthesis, design, integration, and optimization were not included yet.

The area is too broad and complex for the definite selection of quantities, their names, and symbols, but every journey starts with a single step. The proposal with the list of quantities, their names, symbols, and units must be discussed in national and international associations as well as the International Organization for Standardization. Environmental and economic quantities could also be discussed as separate standards because their importance is broader than the area of chemical and process industries.

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standards

Article
Challenges in the Integration of Quality and Innovation Management Systems

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Abstract: Seeking to reduce the number of inconsistencies in their processes, many organisations choose to implement the ISO 9001:2015 quality management standard. Their aim is to improve operational performance while, at the same time, they cope with increased pressures from the market to present innovative products and solutions and from the stakeholders to implement new organizational methods. This work intends to investigate how organisations can leverage ISO 9001:2015 in implementing the ISO 56002:2019 innovation management standard, given that both standards have a high degree of compatibility with each other. For that purpose, meetings were held with senior managers and quality managers of three Portuguese SMEs to discuss the existing potential challenges and gaps in the integration of both management systems. The results point to the existence of a significant set of practices in the field of quality that can support and facilitate the formalization of integrated management systems. Nevertheless, generalization of the results should be avoided, and more research is needed, since the integration of management systems is often conditioned by cost and time related issues. Furthermore, it is disputable whether a company can simultaneously reach a high level of efficiency (brought about by implementing a quality management system) and a high level of innovation (made possible by the implementation of an innovation management system) thus jeopardizing the implementation of an integrated management system.

Keywords: innovation; quality; management system; integration; standardization; ISO 56002:2019; ISO 9001:2015

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1. Introduction

Seeking to reduce as much as possible the number of inconsistencies, waste or nonconformities in their processes, many organisations choose to implement the ISO 9001:2015 quality management standard, aiming to improve their entire operational performance by implementing and promoting the specifications that the standard conveys about continuous improvement and risk-based thinking and adopting a process approach.

In addition, ISO 9001:2015 also conveys a set of seven quality principles that, when instilled and applied in the day-to-day of organisations, increase the likelihood that they will demonstrate to their customers a higher level of excellence and demonstrate the organisations' ability to provide products and services that consistently meet customer requirements through the implementation of the content referred to in their requirements [1].

However, even though they have implemented ISO 9001:2015, what companies sooner or later end up seeing is growing instability in the domains of innovation in their industry, which ends up creating an impasse and a need to be constantly alert and able to respond to the different threats that are being posed to them.

One of the ways organisations can see as a plausible option to maintain and survive in the competitive market where they operate is through the adoption/integration of innovation standards [2]. Currently, many countries have their own innovation standard, which includes recommendations and innovation techniques intended to facilitate the entire process of managing innovation or inherent innovative activities. However, when compared to each other, they show that they focus on different aspects or focus on different themes, with only a few have similarities.

While preparing the most recent version of ISO 9001:2015, two new themes were suggested to complement the existing standard. Risk and innovation were addressed, and it was concluded that innovation management would require the inclusion of a wide range of contents and require all organisations to comply with the innovation requirements if they wanted to have their quality management systems certified. It was then decided that the new version would only include a greater focus on risk management and that the subject of innovation management would be further developed elsewhere [3].

By 2014, the International Organization for Standardization (ISO) set up the ISO/Technical Commission 279, aiming to provide tools, approaches and methods using the holistic approach to managing innovation, its implementation and its interactions with stakeholders in the innovation chain.

Its main objective was to standardise tools and methods dedicated to the field of innovation and in interactions between all actors in innovation management for industrial, environmental and social benefits. The strategies followed pursued the "integration of sustainable development issues in the context of innovation" and the "coherence of an innovative approach with other existing international standards".

From work developed by the ISO/TC 279, a set of five documents was already published:

1. ISO 56000:2020—Innovation management—Fundamentals and vocabulary [4].
2. ISO 56002:2019—Innovation management—Innovation management system—Guidance that guides the establishment, implementation, maintenance and continual improvement of an innovation management system used in all established organisations [5].
3. ISO 56003:2019—Innovation management—Tools and methods for innovation partnership—Guidance provides a guide for innovation partnerships based on an innovation partnership framework and the sample corresponding tools [6].
4. ISO/TR 56004:2019—Innovation Management Assessment—Guidance that helps the user to understand why it is beneficial to carry out an Innovation Management Assessment (IMA), what to assess and how to carry out the IMA [7].
5. ISO 56005:2020—Innovation management—Tools and methods for intellectual property management—Guidance that proposes guidelines for supporting the role of IP within innovation management [8].

The work developed by ISO/TC 279 has as an essential requirement the development of standards according to the ISO Annex SL (a section of the ISO/IEC Directives part 1 that prescribes how ISO Management System Standard (MSS) standards should be made compatible).

ISO 56002:2019 is a guidelines standard following a Type B Management System Standard (MSS) [9,10], whereas ISO 9001:2015 [11] is a requirements standard following a Type A MSS, making incompatible the auditing of an integrated management system that implements these two standards. However, in the scope of the ISO Technical Commission 279, under development (stage 20.00—Preparation—New project registered in TC/SC work programme) is the ISO/AWI 56001 (Innovation management—Innovation management system—Requirements) [12] that will be articulated with the requirements of the ISO 56002:2019 and will follow a Type A MSS. For that purpose, and as starting point for analysis and discussion, in this work, it was considered the ISO 56002:2019, noting the subtlety that it is not a requirements standard but a guidelines standard.

As such, this work intends to investigate to what extent an organisation can leverage ISO 9001:2015 (that it has already implemented) to satisfy ISO 56002:2019 guidelines, given that both standards have a high degree of compatibility, as they follow the structure present in Annex SL. As emphasized by [13], as long as it is possible to identify the similarities between both the innovation management system and the quality management system, it is possible to incorporate innovation management in any type of integrated management system.

Information was gathered from different studies and scientific investigations on the entire scope of the subject under study to analyse the evolution of innovation standards in several countries. Based on this analysis, the potential for integration between quality and innovation management systems was studied, namely in terms of benefits and difficulties associated with this type of integration. Then, a questionnaire was applied to a panel of three industrial companies to identify difficulties and expected benefits with the integrated adoption of ISO 56002:2019 and ISO 9001:2015.

With the results of this evaluation, it was possible to carry out a sustained comparison on the context of innovation of the companies and verify which factors influence negatively and positively the process of adopting this innovation standard. The approach adopted in this study follows the suggestion of [13]: a company should start the integration of an innovation management system by adapting a management system already implemented in the organisation (which is usually the quality management system) and then add additional processes, practices and procedures according to the requirements of the standards underlying the innovation management system.

However, it should be recognized that the integration of both systems is not easy [14]. On the one hand, it is necessary to balance the "free nature" of innovation with the constraints imposed by a management system [13]. In fact, the innovation management field is less well-defined and intrinsically more diverse and uncertain [15,16]. On the other hand, the quality management system is mainly focused on the conformance to standards, while innovation is about breaking new ground [17] such as, for example, the introduction of artificial intelligence into new products [18]. Therefore, companies face a big challenge when trying to integrate both quality management and innovation management systems in a coherent, meaningful and practical way [14].

The work concludes with a synthesis and critical reflection for implementing new solutions for the organisations' innovation processes.

This paper contributes to filling a gap in the literature identified by [2]: the lack of research about how to implement and integrate an innovation management system with other management systems already existent in a company. Since most companies have already implemented at least one management system (e.g., quality management system, environmental management system, occupational health and safety management system), it is important to assess the challenges and clearly design the method of implementation and integration of the innovation management system to avoid conflicts and problems between the management systems and to make the process of integration as successful as possible.

2. From Quality to Innovation

2.1. Historical Background on Quality

Today, it is common to come across several situations where the term "quality" is used. However, it can be associated with different areas, from the price and services provided to the aesthetic appearance, the cost of the product's life cycle, respect for the environment or functional aspects of a product or service.

In the past, although the term was commonly used and relatively easy to recognise, there was a specific difficulty in finding a definition, the main reason being the fact that there were different perceptions and interpretations that everyone had about it.

In 1987, due to the proven lack of uniformity and congruence in the establishment and definition of terms and matters relating to quality management systems, ISO began to create a series of quality standards to improve and promote the growth of organisations [1].

The first standard in the series began as ISO 9001:1987 [19], which focused on the concept of Quality Assurance. It then evolved to ISO 9001:1994 [20], where the updates were based around the concept of preventive actions. Later, ISO 9001:2000 [21] was elaborated, where the concept of Quality Management to improve organisational processes was approached, and eight years later, a new version of the standard would appear, which would only have a reduced number of changes compared to its previous version [22].

This series of standards would come to have as its primary purpose to seek to transmit and describe the base contents, namely fundamental concepts, principles and vocabularies used in the description of contents of other standards of the 9000 standards series (e.g., ISO 9000:2015 [23], ISO 9001:2015 [11], ISO 9004:2018 [24] and ISO 19011:2018 [25]).

2.2. Innovation and the ISO 9001:2015 Revision

As previously mentioned, ISO 9001:2008 promoted continuous improvement and orientation towards organisations that seek to add value to their business model through the implementation and operationalisation of a Quality Management System.

As for the 2015 version, at the beginning of its creation, the intention was to insert two new components, one related to innovation management and the other related to risk management. In the end, the final version only focused on risk management, with innovation management being left aside, under the responsibility of a Technical Committee created to develop the respective regulations and guidelines [3]. This situation happened due to the existence of a discussion and awareness by the ISO members responsible for the standard that, if clauses related to the theme of innovation were added, together with the other clauses related to quality in ISO 9001:2015, they would have to be seen as certification requirements. This requirement would jeopardise the certification of a vast majority of companies that would not present themselves adequately prepared and able to adapt and formalise the quality standard in its entirety, namely in what concerns innovation.

The ISO 9001:2015 standard pointed out that those organisations were free to apply independently developed methodologies to calculate and assess the impact that certain risks have for them (considering the costs of each risk and the time it will take to eliminate/reduce the consequences of the same) [11]. However, [26] argues that two aspects should be seen as crucial to effectively identify and assess any risk, namely the creation of comprehensive risk classification and the creation of a risk management system for innovation, as they allow organisations to ascertain not only the nature of the risk in question but also the reason for its cause.

Ref. [3] also refers to the importance of organisations presenting ambidexterity, that is, being able to innovate simultaneously both at an incremental and radical level, in search of the realisation of continuous improvements and the achievement of operational excellence. Corroborating what had been defended, [3] concludes that there is a relationship between quality management and innovation management, where the level of support that both have in each other is increasingly evident, being the focus and knowledge that both hold and require from customers an inescapable aspect between them.

2.3. Innovation Norms

In recent decades, the topic of “innovation” has incited several discussions in the scientific community as it is increasingly considered an essential element for the survival of organisations in increasingly demanding and competitive markets [27]. As a result, several innovation models have been developed over the years to try to formalise and standardise thoughts and approaches related to innovation [28,29].

The author of [30] argues that the transition from the expanding markets and economic growth of the 1950s to the current and highly competitive global market was reflected in the parallel evolution of management and innovation practices. Moreover, this evolution was accompanied by certain types of innovation models conceived over different generations that sought to be representative of the progress and development of the innovative approaches of the respective era [31].

In a more current perspective, [32] still considers a sixth generation that requires an interaction between innovation systems and networks. In this generation, the central element is the “innovative milieu” defined by the author as “a creative combination of generic knowledge and specific skills, in addition to a territorial organisation and an essential component of the technical and economic creative process". According to [33], sixth-generation models do not focus on internal ideas or closed networks but rather seek an opening to the market, enabling an external generation of ideas that may come from customers or other companies in the area.

However, and even before the sixth generation, there was an attempt to create a model with a more contemporary, adaptable and interactive perspective where R&D was not placed as a permanent or usual starting point for the innovation process. Ref. [34] created a model called the "chain-linked model", whose main highlight was the fact that innovation can start at different stages or originate from various innovative sources. Basically, for the authors of this model, innovation could originate in different ways, either through continuous interactions, such as sporadic or conditional interactions, or as the result of top–down or bottom–up processes, thus eliminating the presupposed associated staticity to the innovation process [35].

Based or not on this model, what was found was that several countries ended up choosing to create an innovation regulation that would help companies in the way they managed their systems, processes, activities or innovation initiatives. As a result, from the European perspective, country-wide and European standards on innovation were developed throughout the last fifteen years, namely UNE 166002:2006 [36] (Spain) (later revised by UNE 166002:2014 [37] and UNE 166002:2021 [38]), NP 4457:2007 [39] (Portugal) (under revision as NP 4457:2021 [40]), BS 7000-1:2008 [41] (United Kingdom) and FD X50-271:2013 [42] (France).

The creation of these standards led to the need to have them unified as an international standard, as described previously, and from that process, the ISO 56000 series was born.

None of the international standards of innovation developed or under development intends to limit the creative process of idealising companies' innovation projects. Instead, they seek to reference some of the best practices that lead to the emergence of a more collaborative environment and language between the different stakeholders in the innovation process. The emphasis is more on collective action and collaborative learning to foster innovation. With the adoption of these standards, a company may find it easier to reduce or even eliminate some of its waste, thus adding more value to its business model [2].

In summary, what was intended with the creation of the ISO 56000 series of standards was to define standards that would transmit a set of references and procedures that would enable the existence of a more collaborative environment that went beyond the national borders of each country. In this way, some of the cultural barriers in certain countries with the power to embrace synergies capable of interceding and transforming industrial sectors would be reduced or attenuated, giving rise to increasingly sustainable industries.

This regulation, in addition to guiding organisations towards creating an innovation policy for the development of new processes/products/services following their organisational objectives, also seeks to make them include and install in the mentality of their employees a set of innovation principles with the power to shape the way they see it, giving them a broader perspective as to its benefits and barriers, thus reducing their resistance to changes and possible imprisonment of ideas.

As it can be implemented in any organisation regardless of its size, area or maturity, this guidance essentially conveys lessons that focus on different areas of action, seeking to facilitate the definition and establishment of objectives and performance indicators to assess the results of its innovation system [3].

As previously mentioned, ISO 56002:2019 is based on the principles of innovation management [5]. It is schematically represented how the structure of the innovation management system should be viewed, relating it to the different clauses of the standard and the PDCA approach.

This standard also refers to the need for an appropriate structure to manage the risks and uncertainties associated with the organisation's market, especially in the earliest stages of its creative processes. The structure that is adopted also allows for an alignment with some international standards, such as ISO 9001:2015 and ISO 14001:2015 [43], enabling a more effective integration, development, implementation, maintenance and continuous improvement of the innovation management system.

The adoption of this standard, together with the innovation tools, facilitates and boosts the innovation process of any company by providing principles that allow it to structure and organise its internal innovation processes, maximise innovation efforts and harness the knowledge and creativity of its employees and those with whom it collaborates externally and make possible an integration with other existing management systems [2].

2.4. Integrated Management Systems

Over the years, there has been an increased interest of organisations in adopting the ISO standards. For this reason, ISO began to pay attention to the need to make possible the adoption and integration of the different systems present in its standards by defining a base structure that would be common among all of them and which is useful for organisations that meet the requirements of two or more management system standards. This interest shown by organisations may be justified based on customers' constant search for better products/services, increased competition between organisations, government regulations and increased concern to reduce costs associated with the business models of each one [9].

However, it is not enough to have the will and interest in implementing them. It also means to be able to implement each management system according to ISO standards. Furthermore, this integration into a single system needs to have an aligned structure and management systems so that it can coordinate its organisational activities and, consequently, increase the motivation of its employees and improve organisational sustainability [44].

An integrated management system can be understood as a "construction to avoid duplication of tasks that seeks to take advantage of the common elements of two or more separate systems, putting them to work together in a single and more efficient integrated management system" [45]. By integrating different management systems into one, organisations can continuously improve their internal processes by starting to perform more effectively and efficiently the management of risks related to the delivery of products and services for both their customers and for any of its stakeholders [46].

According to [45], it is also necessary to pay attention to the fact that the level of systems integration varies depending on the organisation. For example, the degree of integration of a management system initially independent within the company may be conditioned by factors such as its integration strategy, methodology, maturity or internal motivations. In addition, the authors also mention the existence of other types of aspects that may also influence the achievement of the expected success with it, such as the type of industry to which the companies belong and the size that each one has, also relating to effectiveness and sustainability of systems integration with each organisation's resource allocation capacity.

In case an organisation intends to integrate different management systems, [47] proposes the following process:

1. Map key business processes;
2. Analyse business processes using flowcharts;
3. Identify risks—business, environmental, health and safety at work or quality;
4. Cross-reference the clauses of Annex SL or the ISO standards individually;
5. Formulate operational policies that will govern the processes;
6. Develop procedures or other methodologies to control each business process that will define who does what, where and how;
7. Implement controls and communicate to all interested parties;
8. Evaluate the effectiveness of the processes;
9. Review and improve.

According to the authors, any organisation can achieve such integration as to enable the improvement of its global performance, increase the involvement of all individuals at an internal level, reduce document duplication and avoid unnecessary risks by carrying out better risk management more effectively and more efficiently.

However, literature [46,48–50] reports that the creation of integrated management systems, especially in what concerns quality and environment, is not always straightforward, with difficulties in the lack of certification support [51] and difficulties with the management of the organisational culture [52] leading to the need for organisations to make a serious assessment of the costs and benefits associated with the implementation of integrated management systems.

2.5. Integration Barriers between ISO 56002:2019 and ISO 9001:2015

As mentioned previously, ISO 56002:2019 has significant structural similarities with the current ISO 9001:2015 (see also Appendix A), which could serve as a determining, driving and facilitating factor capable of attracting companies that already have ISO 9001:2015 implemented to integrate it, as they would only have to make some changes concerning what they would have previously adopted, namely in clauses 4.4, 6.3, 8.2, 8.3 and 10.2.

Despite the differences noted, most clauses are compatible and can be integrated into a single management system. Furthermore, a good part of each standard can be integrated in a way that makes it possible to make any organisation more consistent and less complex.

The integration of management systems, in general, increases the satisfaction of internal and external customers, improves communication between all levels of management and reduces costs associated with the number of necessary audits. In addition, it was concluded that it also allows unification of objectives, processes and resources; reduces bureaucracy by eliminating duplication of policies, processes and records; avoids duplication; improves the organisations´ overall effectiveness and efficiency and its competitiveness [53].

However, it can be observed that there is a divergent thematic focus in specific points of both documents, specifically in some clauses of requirements 4, 6, 7, 8 and 10.

It is also worth mentioning that there is a difference in clauses (35 clauses in ISO 9001:2015 and 33 clauses in ISO 56002:2019).

Although small, this differentiation may come to be synonymous with the need to assign new responsibilities and roles to avoid conflicts between organisational structures; to start maintaining additional documentation for each standard; and to carry out audits with a higher level of complexity, contrary to what would be expected [47]. A study by [14], focused on the challenges of integrating quality management and innovation management systems in two different Swedish public organisations, concluded that “the current quality management practice is related to development and maintenance of standardisation and leads to a decreased leeway for innovation”. However, it was also possible to perceive, at the same time, that there is “a common expectation and belief [. . .] that innovation and quality management can be handled in parallel and reinforce each other, but it requires active and conscious efforts within the organisations to develop leeway for innovation”.

3. Materials and Methods

Based on the previous analysis, the following work consisted of inquiring ISO 9001:2015-certified companies about the potential difficulties and benefits in integrating the existing quality management system with an innovation management system, according to the guidelines of ISO 56002:2019.

For that purpose, meetings were held with senior managers and quality managers of three Portuguese SMEs (with NACE code 23 (manufacturer of other nonmetallic mineral products), 28 (manufacturer of general-purpose machinery) and 30 (manufacturer of other transport equipment)) to discuss the existing gaps in the integration of both management systems.

The discussion started with the analysis of the Quality Management Systems of the involved companies and a verification of the existing quality and innovation processes and procedures. From there, complementary questions were asked about specific requirements to obtain a clearer perception of the existing actions aimed at specific requirements of ISO 9001:2015, and the clauses that might be most problematic when addressing the implementation of an Integrated Management System including Quality and Innovation were identified.

Using a framework for discussion based on [54], an assessment of difficulties of implementing the integrated management system was made, and the potential benefits that can be achieved from both the internal perspective and from the external perspective were identified and discussed.

The internal benefits and difficulties were analysed from the strategic, tactical and operational perspective, whereas the external benefits and difficulties were analysed from the institutional and stakeholder perspective.

4. Results and Discussion

In what concerns the implementation of an integrated management system, and considering the existent quality management systems of the organisations addressed, the main difficulties foreseen with the implementation of the innovation management system and the underlying integrated management system were the following:

Regarding clause "4. Context of the organisation", the subclause "4.4 Establishing the innovation management system" of the ISO 56002:2019 [5], the standard must be articulated with subclause "4.4 Quality management system and its processes" of the ISO 9001:2019 standard.

The integrated management system may lead to the need to reassess internal communication approaches, paying attention to and promoting a *favourable* culture for the execution of innovation activities. It was mentioned that such promotion should include the existence of an incentive and support for innovation activities such that they are able to not only encourage the dissemination of feedback, suggestions, experiments and learning from past mistakes by all hierarchical levels but also encourage and recognize successful innovative *behaviours* (e.g., creation of motivation policies) and a more proactive approach to people development and training.

Considering collaborations with external entities, even though all the interviewed entities have collaboration with key suppliers, universities and R&D centres, it was necessary to align that collaboration with the overarching innovation vision, monitoring the strategic relevance of these collaborations, both from the internal and the external perspective, especially regarding enhancing knowledge sharing among the parties, as well as a clearer identification of existing skills and resources not only within the organisations but also among the collaborating entities.

In what regards clause "6. Planning", the subclause "6.3 Planning of changes" in ISO 9001:2015 differs substantially from the subclause "6.3 Organisational structures" in ISO 56002:2019. Traditionally, the interviewed organisations rely on traditional project-based product development departments, either in using a push strategy or a pull strategy to address the marketplace. This new approach will reinforce the latter, leading to the need to introduce new creativity mechanisms and the reinforcement of existing cooperation with customers and suppliers in the development of projects and programs. This change must also take into consideration subclause "6.4 Innovation portfolios" in ISO 56002:2019 that will demand the introduction of the concept of portfolio in the organisations, demanding a new analysis dimension that departs from the traditional project/program management approach, and require their alignment with the overarching strategy of the organisation and the underlying procedures.

In clause "7. Support", the introduction of three new subclauses "7.6 Tools and methods", "7.7 Strategic intelligence management" and "7.8 Intellectual property management" will require careful planning in the selection of the tools and methods of innovation that exist in the marketplace, most of them developed by large companies and addressed to start-up-like organisations. Examples include the tools developed by IDEO (2021) for brainstorming or the Design Sprint by Google Ventures (2019) and those that usually do not have a *formal training mechanism* for their implementation in the organisations.

The strategic intelligence management subclause can be supported by “ISO 56006—Innovation management—Tools and methods for strategic intelligence management—Guidance” [55] that is currently in stage 60.00 (International Standard under publication). The analysed companies usually demonstrated *they* had intelligence mechanisms with information provided by stakeholders. However, the ensuing results from this process were not properly systematized nor divulged within the companies.

The intellectual property management subclause can be supported by the “ISO 56005:2020—Innovation management—Tools and methods for intellectual property management—Guidance” [8]. Even though the inquired companies demonstrate that they properly protect the knowledge created, the valorisation mechanisms of the protected knowledge are usually absent, with little evidence of the enforcement due to lack of specialized resources that are required for a proper and effective implementation of these procedures.

In clause “8. Operations”, the main differences lie in subclause “8.2 Innovation initiatives” and subclause “8.3 Innovation processes” of the ISO 56002:2019 standard.

The former is related to the way the organisation manages the initiatives that, although it has similitudes with the clause “8.2 Requirements for products and services” of the ISO 9001:2015 standard in what concerns gathering the internal and external requirements, it does not address other innovation specific issues such as the way how each initiative must be approached.

The latter is related to the way the organisation manages the innovation process, following procedures that enhance flexibility and adaptability of the process. The existing procedures for the design and development of products are aligned with the innovation processes; however, they need to be revised to be aligned with the other mechanisms, especially regarding the subclause “4.4. Establishing the innovation management system”.

To assess the degree of interest and relevance that ISO 56002:2019 presents from the perspective of enquired organisations and based on the analysis made when filling out the questionnaire to assess the organisation’s perception of how it views a possible integration between its QMS and a future IMS, the following results stand out:

In what concerns strategic internal benefits, the inquired organisations reported that it would enable the creation of value and an increase in the organisations’ competitive advantage, enabling the creation of integrated procedures regarding quality and innovation that would enhance continual improvement mechanisms. It would also allow greater transparency and efficiency in the organisations’ functioning, lowering the complexity of the internal management and reducing risks by adopting more straightforward and more focused management systems. However, it would present challenges and difficulties in the overarching strategic management and in the creation and organisation of an integrated management system.

On the functional end of the internal benefits, the main benefits foreseen are concerned with avoiding the duplication of efforts and with the optimized use of resources, since standard continual improvement and systematic innovation actions and methods will be applied, enabling more efficient innovation projects that can be articulated with internal reengineering and cost-reduction actions. Regarding the technological development and the technology transfer mechanisms, it is foreseen that coherent procedures will optimize the value captured from the innovation project results.

However, it is foreseen that an ineffective implementation of the integrated management system may lead to problems that will arise in the mid–long term. This problem is especially relevant since the combination and integration of the different systems is not always clear and usually it lacks a structure upon which the integrated system is built, with problems integrating objectives, processes and resources in the same management system in a coherent way. Moreover, the lack of specialized resources may hamper the operationalization of the integrated management systems, especially due to its scarcity in SMEs.

One final note is related to the cost of performing several audits. Although ISO 56002:2019 is a guidelines standard, in the near term, it is expected to become a requirements standard once the ISO/AWI 56001—Innovation management—Innovation management system—Requirements (currently under development) become approved, leading to the need to have multiple *third-party* audits to certify the integrated management system.

From the operational perspective, the possibility of reduction in the number of procedures and records is the main internal benefit, that, however, clashes with the difficulties foreseen in the implementation of the integrated reports.

In what concerns human resources, the implementation of the integrated management system may lead to improved communication and sharing of *information* between different organisational levels, with a clear definition of responsibilities, especially in what concerns the implementation of innovation projects, and an improved and clearer roadmap in what concerns training activities to be more aligned with the future vision of the organisations. On the other hand, it is feared that, if not properly articulated and implemented, the management system may lead to conflicts due to the overlap of interests and motivations.

Regarding external benefits, it is stated that the implementation of the integrated management system will allow a more effective response to the changes in the marketplace, especially *since* the marketplace strategic intelligence mechanisms, already existent for the QMS, will highlight the innovation roadmap of the industry, providing management with a clearer perspective of the future trends.

The involvement of the stakeholders will be of benefit, transmitting a positive image of the company to the marketplace and providing its customers and suppliers with a platform for the development of innovative solutions that can be integrated and coherent, aligning the supply chain and the introduction of customized solutions to the customers.

5. Conclusions

The results obtained point to the existence of a significant set of practices in the field of quality that can support and facilitate the formalization of integrated management systems including quality and innovation management systems. Nevertheless, it appears that, to ensure a correct and adequate transition to an IMS, companies must follow the guidelines presented throughout ISO 56002:2019 that reveal objective examples of implementation of certain practices, as it categorically explains the key points that should be included in the innovation processes and/or initiatives to ensure the total success of its innovation activities.

Moreover, the analysis of the potential benefits and difficulties resulting from the integrated management systems reveals that most of the problems reside in the lack of qualified resources to support the integration process and the underlying administrative burden on the organisation.

Considering all the information gathered, there is, in fact, an interest and capacity on the part of the companies to proceed with the integration of the QMS with a future implementation of an integrated management system including quality and innovation.

Even though they lack adequate human resources to implement and maintain these systems, the involved companies revealed that they have the appropriate infrastructure and resources to be able to develop innovative systems and mechanisms that increase their value in the market.

However, they must address chronic problems of industrial SMEs in Portugal, such as the promotion of greater involvement of employees in defining objectives and innovation strategies to improve its culture of innovation. The implementation of systematic measurement of the innovation activities must also be pursued so that a company can, over time, compare its activities, technologies, competences, etc. with that of other entities operating in the market to increase its competitive advantage vis-à-vis their main competitors.

As an overall conclusion of the study undertaken, it seems that the perception of the managers of the companies interviewed is that the type of relation between quality management and innovation management systems is synergetic and not conflicting by using the typology of [15]. This means that the combination of quality management and innovation management in an integrated management system contributes to fostering the innovation process within a company, enabling an environment for innovation development [15]. The results seem, also, to contradict the claim of [56] that quality professionals are not very much aware of the innovation phenomena and vice-versa. At least for the case of the three companies studied, although some problems are recognized with the integration of the two management systems, it seems that the companies' managers are aware of the importance of their integration.

Although interesting results have been obtained in this paper regarding the process of integration of an innovation management system in an already existent quality management system of a company, the generalization of the results should be avoided, and more research is needed. Firstly, the integration of management systems is often conditioned by issues related to costs, time and benefits [13]. Secondly, the process of innovation depends on several contextual factors, such as industry, company size, innovation ecosystem, the life cycle of the innovation and role of stakeholders [15]. Finally, whether a company can simultaneously reach a high level of efficiency (brought about by implementing a quality management system) and a high level of innovation (made possible by the implementation of an innovation management system) has been questioned by several authors [14]. If this is not possible, it could jeopardize the implementation of an integrated management system.

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Appendix A

Table A1. Iso 9001:2015 vs. ISO 56002:2019 (based on [5,11]).

ISO 9001:2015—Quality Management Systems—Requirements	ISO 56002:2019—Innovation Management—Innovation Management System—Guidance
1. Scope	
2. Normative References	
3. Terms and Definitions	
4. Context of the Organisation	
4.1 Understanding the organisation and its context	4.1 Understanding the organisation and its context
4.2 Understanding the needs and expectations of interested parties	4.2 Understanding the needs and expectations of interested parties
4.3 Determining the scope of the quality management system	4.3 Determining the scope of the innovation management system
4.4 Quality management system and its processes	4.4 Establishing the innovation management system
5. Leadership	
5.1 Leadership and commitment	5.1 Leadership and commitment
5.2 Policy	5.2 Innovation policy
5.3 Organisational roles, responsibilities and authorities	5.3 Organisational roles, responsibilities and authorities
6. Planning	
6.1 Actions to address risks and opportunities	6.1 Actions to address opportunities and risks
6.2 Quality objectives and planning to achieve them	6.2 Innovation objectives and planning to achieve them
6.3 Planning of changes	6.3 Organisational structures
	6.4 Innovation portfolios

Table A1. *Cont.*

ISO 9001:2015—Quality Management Systems—Requirements	ISO 56002:2019—Innovation Management—Innovation Management System—Guidance
7. Support	
7.1 Resources	7.1 Resources
7.2 Competence	7.2 Competence
7.3 Awareness	7.3 Awareness
7.4 Communication	7.4 Communication
7.5 Documented information	7.5 Documented information
	7.6 Tools and methods
	7.7 Strategic intelligence management
	7.8 Intellectual property management
8. Operation	
8.1 Operational planning and control	8.1 Operational planning and control
8.2 Requirements for products and services	8.2 Innovation initiatives
8.3 Design and development of products and services	8.3 Innovation processes
8.4 Control of externally provided processes, products and services	
8.5 Production and service provision	
8.6 Release of products and services	
8.7 Control of nonconforming outputs	
9. Performance Evaluation	
9.1 Monitoring, measurement, analysis and evaluation	9.1 Monitoring, measurement, analysis and evaluation
9.2 Internal audit	9.2 Internal audit
9.3 Management review	9.3 Management review
10. Improvement	
10.1 General	10.1 General
10.2 Nonconformity and corrective action	10.2 Deviation, nonconformity and corrective action
10.3 Continual improvement	10.3 Continual improvement

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standards

Article

Innovation Opportunity and Challenge of Standardization in Response to COVID-19 Pandemic and the Socio-Economic Impact: A Case Study in Indonesia

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Abstract: The COVID-19 health crisis has disrupted various aspects of life: social, economic and work models in organizations, such as government organizations, private organizations, and businesses. To overcome this situation, a number of appropriate activities are needed to directly overcome the various problems in public health, both preventive and curative. In line with that, activities have also been taken to recover from the impact caused by the COVID-19 pandemic. This paper describes the role of standardization in response to the COVID-19 pandemic, including the business process of formulation and development of standards, conformity assessment procedures, and the role of metrology in providing calibration services. Moreover, the role of the implementation of standards to overcome the socio-economic impact and innovation is also discussed. The method used in this report is based on observation and secondary data. The observation was carried out in Jakarta and surrounding cities, which are representatives of the islands of Java and Bali. A short overview of the literature regarding Coronavirus, the principal role of standardization, regulation, innovation, and its social-economic impact were obtained from secondary data from various sources.

Keywords: COVID-19 pandemic; standardization; conformity assessment; metrology; socio-economic impact; innovation; small medium enterprises (SME) role model

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1. Introduction

The outbreak of COVID-19, which started in Wuhan, China, has become a global problem around the world. On March 11, 2020, WHO declared COVID-19 a global pandemic and it has since threatened public health and life-related systems. It had become a global health and humanitarian crisis. The COVID-19 pandemic affected society at the macro, meso, and micro levels [1,2]. It created significant pressure on the health system needs, especially for efforts to prevent transmission and reduce deaths. Based on the current pattern of the spread of COVID-19, the identification of vulnerabilities and regions of relatively severe impact are dense areas, areas with relatively large informal employment structures, and areas with prominent economic structures in tourism, manufacturing, trade, and transportation sectors. There has been a great pressure on the health care system, especially on prevention, basic and referral health services, health insurance (health security), and health human resources, especially for detection and surveillance, laboratory testing, provision of protective equipment, and medical equipment. The handling of the pandemic and the prevention and curative efforts of COVID-19 have hampered the achievement of key health development targets, such as maternal and child health, community nutrition, and disease control [3]. Muhyiddin et al. [4] reported a review of Indonesia's pandemic and recovery acceleration policies. The most important aspect is that vaccination programs that are already running and have been scheduled must be implemented consequently. The combination of the vaccination program and the LSSR (large-scale social restriction) policy will achieve herd immunity in a relatively short time.

From an economic perspective, COVID-19 has put great pressure on almost all aspects of life. Similarly to the world economy, the Indonesian economy has also been negatively affected by COVID-19. The negative impact was felt by almost all economic actors. People's income and consumption fell sharply as a result of restrictions on people's movement. Investment is estimated to be affected as a result of the disruption to companies' balance sheets due to the decline in revenues and the cessation of several production activities. International trade was affected by the low level of trading activity at the global level, which also led to a decline in commodity prices. The health of the financial sector is also expected to decline. These various disturbances have an impact on macro and development goals. The instability of the world economy has resulted in a decline in the exchange rate and pressure on the domestic economy. The decline in demand due to the decline in people's purchasing power also affected domestic production [5–7].

The COVID-19 pandemic is affecting the economy from the supply side and demand side. On the supply side, companies reduce the supply of raw materials and labor, resulting in unhealthy and constrained supply chains. From the demand side, there has been a lack of demand and decreased consumer confidence in the products. SMEs have a significant impact on COVID-19. SMEs are very vulnerable to being affected by business disruptions, because of their frequency of use being directly related to tourism and transportation, as well as culinary industries that require fast suppliers, all of which have been significantly affected by COVID-19 [8,9]. For public and private organizations, a crisis such as a pandemic is a strategic challenge, and the associated disruption of demand and capacity, increased uncertainty, and financial instability forces a reassessment and restructuring of business operations [10,11]. Managerial attention is required to assess how the disruption affects customers and employees [12,13].

To face a huge impact both from the health and economic perspective, the government needs to make policy responses quickly and correctly. Learning from the steps taken by various countries, the policy response to mitigate the impact of COVID-19 can be divided into four stages. The first is to strengthen the health sector, the second is to protect the public and the business world, the third is to reduce pressure on the financial sector, and the fourth is the recovery program, i.e., economic resilience and recovery of people's lives after the COVID-19 pandemic. Related to this program and its activities, standardization as part of national management plays a specific role, not only in handling the pandemic in relation to health problems and supporting facilities but also for innovating activities for responding to the need for a new business model and supply change, which is very important for strengthening national competitiveness [14].This paper will report the challenge and role of standardization in response to the COVID-19 pandemic through changes to the business process of formulation and development standards, conformity assessment procedures, and the role of metrology in providing calibration services, as well as the role of the implementation of standards and innovations to overcome the socio-economic impacts. The method used in this report is based on observation in Jakarta and surrounding cities and secondary data from various sources.

2. Literature Review on Pandemics and the Role of Standardization

The Coronavirus pandemic by the World Health Organization (WHO) has been named Coronavirus-disease 2019 (COVID-19). This virus according to ICTV (the International Committee on Taxonomy of Viruses) is categorized as "Severe acute respiratory syndrome Coronavirus 2 (SARS-CoV-2)". This virus belongs to the order Nidovirales, family Coronaviridae, subfamily Orthocoronavirinae, which consists of four types, namely Alphacoronavirus, Betacoronavirus, Gammacoronavirus and Deltacoronavirus [15]. The severe acute respiratory syndrome has caused morbidity and mortality at an unprecedented scale globally. Scientific and clinical evidence is evolving on the subacute and long-term effects of COVID-19, which can affect multiple organ systems. Early reports suggest residual effects of SARS-CoV-2 infection, such as fatigue, dyspnea, chest pain, cognitive disturbances, arthralgia, and decline in quality of life. Cellular damage, a robust innate immune response with inflammatory cytokine production, and a pro-coagulant state induced by SARS-CoV-2 infection may contribute to these sequelae. COVID-19 is now recognized as a multi-organ disease with a broad spectrum of manifestations [16–19].

The very fast speed of the spread of the COVID-19 pandemic gives an indication that the characteristics and dynamics of the Coronavirus are different from previous viruses. It depends on many factors, such as physical condition (humidity, temperature, and climate) and the biological ecosystem. Indonesia is a humid tropical country that can be a good habitat for various microorganisms, including viruses and their variants. The combination of geographical conditions, humidity, and air temperature can create opportunities for variations in micro-climate. The existence of periodization and a relatively high intensity of sunlight can cause virus mutations, so that the opportunity for the emergence of various mutants or new variants is very large [20]. In the history of pandemics affected by the virus, the fact shows that a mutation of the virus leads to different health impacts. Table 1 gives an illustration of virus types and the number of deaths in different periods from 1918–present.

Table 1. Virus type and the number of deaths in different periods.

Periods	Name	Type	Death	Reference
1918–1919	Spanish Flu	H1N1 Virus	More than 50 M	[21]
1957–1958	Asian Flu	H2N2 Virus	1.15 M	[22]
1968–1970	Hong Kong Flu	H3N2	1 M	[23–25]
1981–present	HIV/AIDS	Virus HIV	32 M (estimated March 2020)	[26]
2019–present	COVID-19	Coronavirus	4.8 M per 5 Oct 2021	[27]

Although each viral pandemic event has different characteristics, such as the 1918 flu pandemic and the 2003 SARS bird flu pandemic, in general, the control is generally classified into several actions, each of which has a different level of risk. As illustrated in Table 2, the pandemic control hierarchy can be divided into five levels [28]. Some countries perform this in a different manner. At the first level, the action taken is the use of personal protective equipment (PPE). At this level, the use of masks, washing hands, and maintaining distance are important acts and this is the initial stage of prevention. The next level is controlled with administrative control. At this stage in Indonesia, for example, the implementation of restrictions on movement and activities of people such as LSSR (large-scale social restrictions), setting office hours, work from home (WFH), and work from office (WFO). Third, at the engineering controls level, control is carried out by providing infrastructure such as facilities for isolation for infected people and provision of treatment facilities. At the fourth level, substitution is carried out, namely the act of removing dangerous pathogens (hazard) and the fifth level is the elimination action, which aims to eliminate the pathogen. For actions levels four and five, this requires a more comprehensive study and for COVID-19 there are not many publications that report this action.

Table 2. The control hierarchy for pathogen and chemical hazard.

No	Hierarchy Control	Goals	Effectiveness
1	PPE (personal protective equipment)	Protect the worker: people with PPE	Less effective
2	Administrative control	Change the people at work	
3	Engineering control	Isolate people from the hazard	
4	Substitution	Replace the hazard	
5	Elimination	Physically remove the hazard	Most effective

Ref: adapted from AVMA [28].

In evolving prevention action, the utilization of vaccines plays an important role [29]. A considerable number of SARS-CoV-2 preventive vaccine projects were initiated shortly after the reporting of this virus, including technologies that generate an inactivated virus vaccine, viral protein subunits vaccine, messenger RNA (mRNA) vaccine, DNA plasmid vaccine, and recombinant human adenovirus type 5 (rAd5) or simian adenovirus type 26 (rAd26) expressing SARS-CoV-2 spike protein, a non-viral replicating vector expressing SARS-CoV-2 protein vaccine, and also replicating viral vector expressing SARS-CoV-2 protein vaccine. So far, there have been at least 30 announced vaccine projects globally and vaccines derived from mRNA, expression using recombinant adenoviral vectors, and inactivated viruses have already gained regulatory approvals in certain countries [30,31]. Wang et al. [32] gave a systematic review of therapeutic development and application including the following areas: epidemiology, virology, and pathogenesis, diagnosis, use of artificial intelligence in assisting diagnosis, treatment, and vaccine development. With the necessary efforts to pursue widespread vaccination, policymakers face a difficult balancing act as they seek to nurture the recovery through efficiently allocated fiscal support while safeguarding price stability and fiscal sustainability. Policymakers can also help entrench a lasting recovery by undertaking growth-enhancing reforms and steering their economies onto a green, resilient, and inclusive development path. Prominent among the necessary policies are efforts to lower trade costs so that trade can once again become a robust engine of growth [33]. Farzanegan et al. [34] give a critical review of globalization and the outbreak of COVID-19.

The government took action to recover the pandemic with three groups, namely enabling the environment, improving productivity, and enacting the job creation law. The first activity focused on improving the business climate, increasing competitiveness, and economic resilience through improvements in the food, energy, and infrastructure sectors. To increase productivity, there is a focus on improving business sectors that have the potential to support the performance of the national economy, including the revitalization of manufacturing, tourism development, as well as empowerment and formalization of micro, small and medium enterprises. As an effort to improve the regulation, the implementation and enforcement of job creation law become one of the vehicles for harmonizing various laws and existing regulations. Standardization and conformity assessment play an important role in this harmonization. Furthermore, one of the most important aspects of harmonization of regulations is the clustering of types of businesses providing goods and services based on the level of risk. The greater the risk, the more stringent regulations are carried out, for example, inspection, certification by third parties, and distribution permits, etc., while for low-risk products, only self-declaration and registration are required [3,35].

According to UNIDO [36], the role of standardization is very important in dealing with the COVID-19 pandemic. As shown in Table 3, standardization including part of the quality infrastructure helps reduce the negative impact of the pandemic crisis and ensures the provision of essential services. This includes quality infrastructure, where standardization and conformity assessments function to ensure the need for relevant standards, accurate measurements (metrology), and guaranteed reliable test results through accreditation. The standards ensure that the technology used in patient care is safe and all users are protected.

Sustainable development goals (SDGs) are often used as a reference and as a holistic indicator. The SDGs are a shared global agenda that all countries have committed to implementing. According to UNIDO, the existence of this pandemic has a very significant impact related to SDG 2 (famine alleviation); SDG 3 (healthy lives and well-being for all); SDG 8 (economic growth and employment); SDG 9 (infrastructure development, industry, and innovation); SDG 12 (responsible consumption and production) and SDG 17 (partnerships to achieve all the goals of the SDGs). In detail, the impact of the pandemic and the role of standardization is depicted in Table 3 [36,37].

According to the ITC (International Trade Center) [38] in its report "Standards support for small businesses during COVID-19" describes the role of standards in helping the SMEs, for fostering competitive, resilient, and sustainable businesses. ISO management standards that are appropriate for this goal are (1). ISO 22313:2020 Security and resilience—Business continuity management systems—Guidance on the use of ISO 2230;

(2). ISO/TS 22318:2015 Societal security—Business continuity management systems—Guidelines for supply chain continuity; (3). ISO 22320:2018 Security and resilience—security and resilience—Organizational resilience—Principles and attributes; ISO 31000:2018 Risk management—Guidelines; (6). ISO 56002:2019 Innovation management—Innovation management system—Guidance; (7). ISO 45001:2018 Occupational health and safety management systems—Requirements with guidance for use; (8). ISO 22000: 2018 Food Safety Management System; and (9). ISO 9001:2015 Quality management systems—Requirements [39]. Another ITC report "The SME Competitiveness Outlook 2021" identifies key areas where small businesses with limited resources can invest to seize opportunities of the green transition, and how business-support organizations, governments, lead firms in value chains, and international organizations can empower small firms to be competitive, resilient and sustainable [40].

Table 3. The role of standardization in the fight against COVID-19 pandemic [36].

Policy	Standards	Accreditation	Metrology	Conformity Assessment	Enterprises
Quality Policy Laboratory Policy	Medical equipment/ protective gear (medical), laboratory standards, business continuity, emergency management, quality control techniques, health, safety and hygiene, sanitation and waste management	Attestation of technical competence International/ mutual recognition	Accurate measurement for reliable testing, quality and accuracy of laboratory tests	Health care facilities and testing laboratories, quality control of medical supplies, medical testing for COVID-19, development of new medication/vaccines, market surveillance and inspection	Shift to produce medical equipment/ protective gear, business continuity, enhanced sanity protocols, avoid disruption of essential inputs to global value chains

3. Methods

This case report is carried out based on the research design as shown in Figure 1, which consists of the scope of work, data collection, data validation, data analysis, narrative description and discussion, conclusion, and suggestion. Data collection has obtained the observation, interview, and secondary data from regulation release, official report, webinars, journal, and other publications. Table 4 describes the data collection, subject of observation and data validation. Part of the data was validated by cross-references, consultation with key people, experts, and role models. The government's strategies and policies in dealing with the pandemic, including economic recovery policies, are discussed. The role of standardization and conformity assessment in dealing with COVID-19 is based on global trends and several recommendations from UNIDO [36]. The implementation of standard management systems, for recovery and the continuing development in the middle term period, s is also analyzed. Some cases of practical businesses and implementation of regulation and standardization were also directly observed, through interviews, and consultations with some experts, regulators, business actors, and conformity assessment institutions. Furthermore, efforts to strengthen competitiveness and innovations are discussed based on data from the testimonies of several role models.

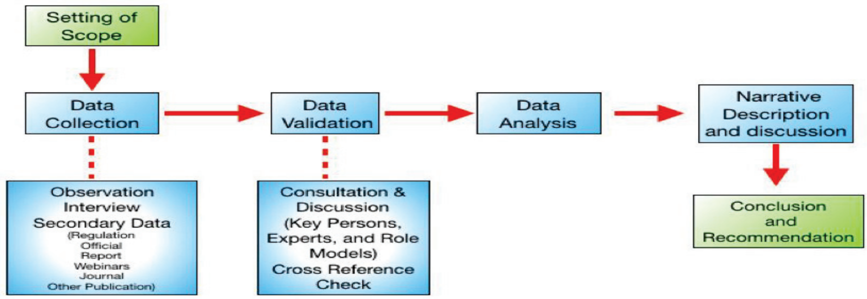

Figure 1. Research design.

Table 4. Data collection, subject-related topics, and data validation.

No	Data Collection	Subject, Related Topics (Number)	Data Validation	Location
1	Observation Webinar Talk show FDG Press release	Standard development (7) Accreditation and conformity assessment (9) Metrology (3) Innovation (15) Regulation (12)	Direct asking of questions	Jakarta Bogor Tangerang
2	Interviews with role model from selected SME	SMEs (21) with following products (medical equipment and device, cloth, food, batik machinery, sport equipment)	Government officer from BSN and the Ministry (industry, trade, agriculture, maritime and fisheries)	Tangerang Bogor Makassar Palembang East Java DIY
3	Secondary data (journal, official report, other publication)	COVID-19 pandemic, standardization, accreditation, metrology, conformity assessment, economic and business, regulatory and policies, innovation	Through comparative analysis of article in journals and other publications	-

4. Results and Discussion

4.1. Role and Challenges of Standardization, Conformity Assessment, and Metrology

4.1.1. Role and Challenges of Standard Formulation and Development

Standardization in dealing with the pandemics plays an important role, especially to ensure safety, quality and traceability. Product standards must especially include medical equipment such as respiratory protection devices, and body protective equipment, such as medical gloves, medical face masks, personal eye protection, and others. Because the existing standard is not fully available for supporting activities during pandemics, it is still necessary to develop new standards obtained by adopting international standards or by modifying international standards processes that are adapted to Indonesian conditions. In developing standards, several things should be considered, including the recognition and acceptance of standards of systems between countries. The acceptance of equality of standards among trading partners (business to business) is considered important to mobilize the demand for medical equipment, which needs a relatively short time.

In general, standards are formulated based on needs assessment and carried out based on the consensus to agree with draft standards among stakeholders and also to refer to scientific evidence. In order to obtain a broad acceptance among stakeholders, the process of the formulation of national standards in accordance with the WTO code of good practice must meet a number of basic principles; ensure transparency, openness, impartiality and consensus, effectiveness and relevance, and coherence, and to address the concerns of development opportunities [41]. To apply these norms, the development of the national standard of Indonesia (SNI) is carried out through the following formulation stages: (1.) planning of national program for standard development, based on needs analysis and prioritizing, (2.) drafting the SNI draft standard, (3.) depth analysis and assessment through technical meetings, (4.) consensus meetings for the public poll, (5.) public pool and discussion of the results of the opinion poll, (6.) final determination and publication of SNI. The total time required for this process is divided into four types; type I normal track (13 months), type II fast track (9–12 months), type IIIurgent needs (4 months), and type IV amendment (5 months) [42].

The increasing need for standards as a result of increasing activities in dealing with the COVID-19 pandemic and the existence of a health protocol system during the pandemic has encouraged accelerating services. In terms of standard development, the process of accelerating standard formulation has been carried out, teleconferencing in the formulation of standards (virtual), and developing a program for formulating standards on an urgent track which needs a much shorter time than around 4 months. Mostly the adoption of international standards used this track. There are some international standards that are very important for supporting the activities during the pandemic, as listed in Table 5.

Currently, the availability of the national Indonesian Standard (SNI) related to medical devices and sanitation is as follows: protective clothing 31 standards, hand sanitizer 14 standards, medical gloves 13 standards, ventilator 13 standards, eye protection 6 standards, respiratory protection 4 standards, medical mask 4 standards, and protective gloves 3 standards. In the year 2020 more than 13,000 national standards are available [42].

To support the laboratory management system, medical laboratory management standards are available, namely ISO 15189, ISO 22367, and ISO 14971. These standards are important for evaluating the safety and valid diagnostic test results for the SARS-CoV-2 Coronavirus. To support laboratory testing activities, currently, more than 1700 laboratories have implemented SNI ISO 17025. Standardization of testing laboratories is needed to ensure that product testing for medical equipment is carried out correctly and provides reliable results so that it can respond to the COVID-19 pandemic effectively and on target. For certain laboratories that work with pathogenic biological objects, the application of the ISO 35001:2019 laboratory biorisk management system is very important, especially to ensure the safety of laboratory personnel working with COVID-19 [43]. When handling a pandemic, preventive measures in an industry or organization can be assisted by implementing an occupational health and safety management system, such as ISO 45001. The application of this standard is very important to maintain occupational health and safety, reduce risks in the workplace, and create safer working conditions against transmission of COVID-19 [39].

To support the food processing industry, the implementation of a food safety management system based on SNI ISO 22000 and HACCP (hazard analysis and critical control points) is the key to ensuring food safety. No less important in handling the pandemic is the application of the ISO 14000 environmental management system standard. This standard will be used as a vehicle for better management of the waste generated as a result of the increased use of disposable protective equipment, such as protective clothing, disposable gloves, and medical masks.

During the pandemic, it was known that many industries were affected as a result of the decline in economic activity. The implementation of risk management standards is needed to strengthen companies' resilience. ISO 31000 has been carried out for a long time in many organizations and companies and has been proven to be able to overcome the crisis. Likewise, during the pandemic and recovery period, the application of this standard is vital as a guide for the design, implementation, and maintenance of risk management. With the combination of the application of other management standards such as ISO 9001, which is quite popular in its application in Indonesia, the resilience of the company or organization improves. With the implementation of this standard, the company is better prepared to face the negative impact of the crisis. Strengthening company performance in times of crisis can also use standards for security, resilience, and business continuity management (ISO 22301, ISO 22395) and emergency management (ISO 22320, ISO 22316). This standard in several countries has proven to play an important role in dealing with the COVID-19 pandemic. Further implementation of these standards is not only important in the short term, but also in the medium and long term.

Table 5. ISO standard related to medical devices [39].

No	ISO Standard	Thematic Subject of Standard
1	ISO/PAS 45005:2020	Occupational health and safety management—General guidelines for safe working during the COVID-19 pandemic
2	SO 13688:2013/AMD 1:2021	Protective clothing—General requirements—AMENDMENT 1
3	ISO 80601-2-12:2020	Medical electrical equipment—Part 2–12: Particular requirements for basic safety and essential performance of critical care ventilators
4	ISO 20395:2019	Biotechnology—Requirements for evaluating the performance of quantification methods for nucleic acid target sequences—qPCR and dPCR
5	ISO 80601-2-74:2017	Medical electrical equipment—Part 2–74: Particular requirements for basic safety and essential performance of respiratory humidifying equipment
6	ISO 80601-2-79:2018	Medical electrical equipment—Part 2–79: Particular requirements for basic safety and essential performance of ventilatory support equipment for ventilatory impairment
7	ISO 80601-2-70:2020	Medical electrical equipment—Part 2–70: Particular requirements for basic safety and essential performance of sleep apnoea breathing therapy equipment
8	ISO 80601-2-84:2020	Medical electrical equipment—Part 2–84: Particular requirements for the basic safety and essential performance of ventilators for the emergency medical services environment
9	ISO 10993-1:2018	Biological evaluation of medical devices—Part 1: Evaluation and testing within a risk management process
10	ISO/TS 16976-8:2013	Respiratory protective devices—Human factors—Part 8: Ergonomic factors
11	ISO 18562-1:2017	Biocompatibility evaluation of breathing gas pathways in healthcare applications—Part 1: Evaluation and testing within a risk management process
12	ISO 18562-2:2017	Biocompatibility evaluation of breathing gas pathways in healthcare applications—Part 2: Tests for emissions of particulate matter
13	ISO 18562-3:2017	Biocompatibility evaluation of breathing gas pathways in healthcare applications—Part 3: Tests for emissions of volatile organic compounds (VOCs)
14	SO 18562-4:2017	Biocompatibility evaluation of breathing gas pathways in healthcare applications—Part 4: Tests for leachables in condensate
15	ISO 80601-2-80:2018	Medical electrical equipment—Part 2–80: Particular requirements for basic safety and essential performance of ventilatory support equipment for ventilatory insufficiency
16	ISO 19223:2019	Lung ventilators and related equipment—Vocabulary and semantics

4.1.2. Role and Change of Business Process of Accreditation and Conformity Assessment

One of the important pillars in the national quality assurance system is accreditation. Accreditation activities are very important in supporting the application of standards so that the conformity of products, services, processes, and management can run in accordance with the requirements and standards applied. The National Accreditation Committee (KAN) carries out the function of providing formal acknowledgment and approval of the integrity and competence of the Conformity Assessment Body (CAB) to carry out conformity assessment activities. The CABs include test laboratories, certification bodies, inspections, and calibrations.

Currently, most of the accreditation processes are carried out by test and calibration laboratories. It is intended that the results of laboratory testing are valid and reliable and meet the required standards. Laboratory accreditation also ensures that human resources working in laboratories are competent. Likewise, the professional and competent management of the laboratory is able to provide various testing services and several other needs related to handling the pandemic.

During this pandemic, many innovations have been produced from within the country. Because they are generally new products, accreditation of product certification bodies and test laboratories is very necessary to ensure product safety and also to increase public confidence in domestic innovation products.

In relation to the global COVID-19 pandemic, accreditation to CAB by an accreditation agency that is a member of an international accreditation organization is very important, to ensure the compatibility of the use of certificates, whose recognition is needed globally. It is also aimed at facilitating the cross-border mobilization of products and services related to medical devices, testing kits, and items for personal protection. Lack of recognition of testing laboratories, for example, can disrupt the smooth flow of trade.

Internationally recognized certificates from CABs in Indonesia are obtained through KAN recognition by the international accreditation organization ILAC (International Laboratory Accreditation Cooperation), following the MLA (mutual recognition arrangement) scheme, and from the International Accreditation Forum (IAF) through the MRA (multilateral recognition arrangement) scheme. The National Accreditation Committee (KAN) continues to make tangible contributions to government programs. Currently, KAN has 13 internationally recognized accreditation schemes.

In response to the COVID-19 pandemic, the accreditation process is faster and has already been performed successfully in more than a year and a half of this pandemic through remote, virtual assessment, applying for digital accreditation, remote assessment, and remote auditing Following assessments by technical committee meetings are conducted virtually. In general, virtual assessment methodologies can also be improved. To maximize accreditation services, recently, KAN also released a digital service system, the KANIA digital service, by utilizing artificial intelligence (AI), to make it easier for the public to attain the best service. KANIA is embedded in platforms that are popular in the community, such as WhatsApp, FaceBook Messenger, Line, and Telegram, which can be accessed 24 h, 7 days a week. This program can make it easier for conformity assessment and fulfills the needs of the customer [43].

Accreditation serves are comprised of CABs from the western part of Indonesia (Sumatra) to the eastern part of Indonesia (Papua). The CABs have involved the testing laboratories, calibration laboratories, inspection agencies, certification bodies for quality management systems, occupational health and safety management systems, laboratory biorisk management systems, information security management systems, education organization management systems, product certification institutes, and proficiency test operators. In 2020, around a total of 2177 CABs have been accredited by KAN, which consists of 312 certification bodies, 114 inspection bodies, 1727 laboratories, and 24 proficiency test providers.

In regard to supporting conformity assessment for CABS dealing with a pandemic, KAN has delivered accreditation services for around 70 laboratories and clinics based on

ISO 15189, 100 testing laboratories based on ISO 17025, 40 calibration laboratories based on ISO 17025, five laboratory external quality assurances (PME) based on ISO/IEC 17043, two inspection agencies based on ISO/IEC 17020, and two medical device management system certification bodies based on ISO/IEC 17021. To support safety for medical laboratories, a new scheme is also implemented, which is a laboratory biorisk management system based on ISO/IEC 35001.

The remote audit is also the best choice during the pandemic for most conformity assessment bodies, which releases certificates of the quality management systems, management systems for education organizations, anti-bribery management systems, information security management systems, and product certification. The remote audit is carried out without visiting the location, either in whole or in part, by utilizing information and digital technology. This certification remote audit mechanism is conducted through communication media such as document sharing according to audit needs, through document links and online meeting applications that are mutually agreed with customers.

All activities of conformity assessment were in line with the recommendation of ISO's Committee on Conformity Assessment (CASCO). This recommendation is based on a global survey conducted among the members of ISO/CASCO Strategic Alliance and Regulatory Group (CASCO/STAR) to collect their experience of coping with the COVID-19 pandemic. The key findings from the survey are focused on maintaining business continuity and replacing on-site activities with remote activities. The remote activities are understood as activities within the process of conformity assessment or accreditation, which do not require the physical presence of the assessing personnel at the site of the object of assessment. Remote activities are mainly used as determination activities but can contribute to all functions of conformity assessment, such as virtual meetings (with internal staff or with external clients and stakeholders), web-based document review, remote auditing, assessing and evaluating by ICT, review and decision making by electronic communication (e.g., by circular emails or web-based voting), and e-learning or webinars [44].

4.1.3. Role and Change of Business Process of Metrology and Calibration

In fulfilling the suitability of the characteristics of a product, a series of physical, mechanical, biological, and chemical properties tests are required according to the desired standard. Metrology provides assurance of reliable measurements as the basis for scientific research, technical development, and production. The national metrology (national standard for units of measure) mandated by Law No. 20 of 2014, must be the highest reference for measurement in Indonesia. The task of this standard is to provide, develop, maintain, and disseminate units' standards.

National metrology is needed to support product testing laboratories to ensure that goods, services, and processes meet product quality, environmental, health, and safety requirements, and meet consumer needs and expectations. The level of conformity with the requirements is largely determined by the level of accuracy of the test equipment that must be traced to the international system of units of measure (BIPM) to increase international recognition and acceptance. Thus, users will be able to take advantage of it to expand access to global markets.

For international recognition of national metrological capabilities, all national standards of measurement units must be traced to the international organization BIPM (International Bureau of Weights and Measures) based in Paris. Indonesia's current position has received BIPM recognition for as many as 135 units of measure; for laboratory services currently providing services, there has been as many as 388 calibration service environments. The number of certificates that have been issued is 1157 per year for more than 500 laboratories [42].

In dealing with COVID-19, metrology is very important because chemical and biological measurements require high accuracy and play an important role during the pandemic, especially for reference material standards (CRM). The ability to accurately measure nucleic acids is crucial for COVID-19 molecular testing, which detects the Coronavirus' (SARS-CoV-2) genetic material (RNA) using certain techniques. The Consultative Committee on the Quantity of Material CCQM) Working Group on Nucleic Acid Analysis has launched a fast-tracked inter-laboratory study for SARS-CoV-2 RNA genome measurement [44,45].

The traced test results will become a compatible database for various uses of test results so as to increase user confidence. The potential for falsification of data that sometimes occurs will be avoided. The government in handling pandemic cases urgently needs accurate measuring tools, including day to day tools such as thermometers, sphygmomanometers (blood pressure gauges), oxygen flow meters (respirators), fluid flow meters (drugs), and others. All measurement results must be reliable and reliable.

To enhance the metrological service to the stakeholder, the development of a digital best service called SPARTA will be made to efficiently reach the laboratories from Sumatra to Papua. This system is directly related to the task of disseminating SNSU through calibration services. Likewise, for calibration services, remote calibration and analysis support are also carried out on calibration records from service users. The digital service system not only improves the calibration and proficiency testing services but also implements bureaucratic reform that emphasizes efficient and transparent services. The users can more easily access services and can interact with service officers. The information on types of services and prices will be more accessible, and the registration process and process monitoring by customers will also be easier, so as to provide certainty and satisfaction for customers. In these systems information on measurement and calibration services covers six areas of measurement, namely mass and related quantities, length, acoustics and vibration, temperature, electricity and time, and radiometry and photometry. Meanwhile, the proficiency test service covers the quantities found in the field of chemical metrology measurements [42].

4.2. Challenges of Innovation for Medical Device, Diagnostic, and Therapy

The pandemic prompted extraordinary interest in innovation, including calls to inspire, initiate and coordinate innovations beyond those already designed and implemented. Some of these initiatives were global or national in scope. The innovation is mostly very clear in the development of a new product, service, process, and business model. The acceleration of change on business models and services is affected by the available digital and information technology infrastructure.

The business model in several sectors, such as education, trading, logistics, etc. has developed rapidly. Innovation in the product, in general, consumes more time, because the safety aspect and technical performance requires a serial test to be completed with a standard or another requirement. In Indonesia, the innovation during the pandemic focused in general on the field of medical care.

In order to support efforts to prevent the spread and transmit, and to overcome the increasing outbreak of Coronavirus-disease 2019 (COVID-19) in Indonesia, the government through the Ministry of Research and Technology/National Research and Innovation Agency plays an active role in integrating, aligning, coordinating, and synergizing research and innovation programs to deal with the COVID-19 pandemic quickly. One of the efforts made is to carry out research, development, assessment, and application activities in a relatively quick time. There are five technological innovation programs and groups from the COVID-19 Research and Innovation Consortium Team for the prevention of COVID-19, namely prevention, screening and diagnostics, medical devices and supporters, drugs and therapy, and multicenter clinical trials (Table 6) [46].

Almost all the results of the innovations are from new products, and therefore for their implementation they must fulfill security requirements. For this, the role of standards in supporting product innovation is very important. In addition, the availability of testing laboratories must be available, including the calibration laboratories, to ensure the traceability of measurement equipment. If the standard is not available, then a new standard is developed, either formulated by oneself or by adopting international standards from ISO, IEC, and other organizations of standards. The trend of the development of technology will evolve due to the high demand for certain products and mostly it is the end-user involved in the setting of technical specifications. Increased end-user involvement, especially in medical devices and supporting policies, are needed for the acceleration of the development of technology and innovation. However, these potential developments need to be discussed alongside the ethical considerations around social exclusion, collection of and access to data, and privacy, as well as issues related to intellectual property [47].

Table 6. The innovation products to the prevention of spread, handling support, screening and medical diagnostic, and therapy for combating pandemic COVID-19 [46].

No	Preventing of Spreading	Handling Support	Screening and Diagnostics	Medicinal and Therapeutic
1	Rapid diagnostic test microchip	RAISA TIARA Robot	Viral Transport Medium	Convalescence Serum
2	Rapid Diagnostic Test RI-GHA	RAISA BCL Robot	VTM (Viral Transport Medium)	Herbal Flu Imboost
3	Real Time PCR Test Kit BioCov-19	Decontamination Robot	Plasmid Eijkman Control for COVID-19 (pECoC-19)	Quinine Pill
4	Autonomous UVC Mobile Robot	Smart Syringe Pump	Robot RAISA	Anti-COVID-19 Serum
5	OST D	Emergency Ventilators	Mobile Laboratory BSL-2	Mesenchymal Stem Cell
6	Herbal Hand Sanitizer	Powered Air Purifying Respirator	Flocked Swab	Convalescence Serum
7	Insert Mask	Ventilator Vent-I	Sequence Protein S SARS CoV 2	Herbal Flu Boost
8	Air Cleaner	Venindo V01	AI based Medical Imaging System	Quinine Pill
9	Portable Air Purifier	Venindo R03	Smart Biosafety Swab Chamber (BCL-UGM)	Anti-COVID-19 Serum
10	Touchless Mobile Handwasher	GLP-HFNC-01 (High Flow Nasal Cannula)	GAMA Swab Sampling Chamber	
11	N95 Mask Sterilization Box	Cov-Watch	Platform Digital (Cared+)	
12	HR COMED	Aero Dental Suction Unit	Radiograph Sinar X-Digital	
13	APD: Lab-Scale Natural Nano Fibers	Smart Telemedicine Robot “Win-MTA”	Swabidarity	
14	PPE Level 3 and 4	Servant Robot	PCR Isothermal Lamp 2	
15	H2 (Health	Robot Representative Doctor (Doper)	Electronic Nose (E-Nose)	
16	Isothermal	Low-Cost Mobile Ventilators	WGS (Whole Genome Sequencing) SARS-CoV-2	

4.3. Challenges of Standardization Regarding the Socio-Economic Impacts

Based on very valuable experiences during the pandemic, to accelerate economic recovery, and to strengthen national competitiveness and independence, the role of standardization needs to be strengthened. Among the most crucial factors is the availability of standards that are able to answer market needs and government policy needs. Standard development can be directed, among others, to support the supply chain in raw materials or supporting components for manufacturing. About 30 percent of Indonesia’s non-oil and gas imports come from China, which is the largest import. The dependence on industrial raw materials, which were not available during the pandemic, has impacted various important industries. Standardization is needed to provide a reference for local suppliers and also to support the ability to compete with imported raw materials. It is recognized that users, especially the manufacturing industry, still need time to adjust to their existing manufacturing processes, for technical and economic feasibility. Another benefit of the effort to be self-sufficient in raw materials is the creation of new supply chains, business fields, and employment opportunities, which, in the end, can strengthen the national industrial structure. This condition will also invite the research and innovation national agency to drive to all research centers, universities and private sectors to contribute to research, development, and technical-economical assessments in various aspects of production, such as processes, manufacturing, testing, and new product development. To support this effort, it is necessary to analyze data related to industrial needs and data on the development of imports of raw materials.

The impact of COVID-19 hit SMEs significantly, which became very vulnerable due to being affected by business disruptions. SMEs' lack of resilience and flexibility in dealing with this pandemic is due to several things, such as low levels of digitization, difficulties in accessing technology, and lack of understanding of survival strategies in business. The recovery of SMEs has also become an important priority because SMEs have a strategic value for creating family income and employment. There are around 64 million SMEs, mostly located in Java. SMEs in Indonesia employed more than 110 million workers. One of the important aspects in fostering the SMEs is advocation for the implementation of standards. During advocation activity, the role model of SMEs in implementing standards will be set up in several locations across all provinces in Indonesia (Figure 2). There are around 707 SMEs, as role models have been advocated, including 452 SMEs in the food sector and 255 non-food SMEs that are spread across 28 provinces. A part of this advocation has been the facilitation of 98 SMEs in obtaining SNI certification, including certification maintenance [8,42].

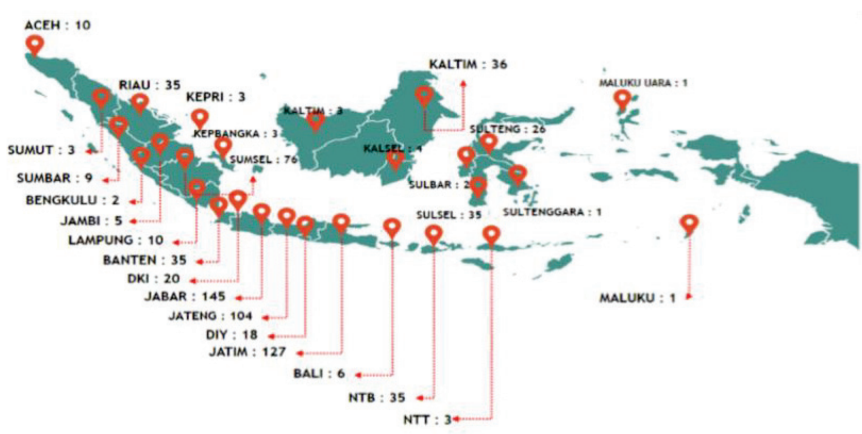

Figure 2. Fostering SME role models in the application of standards in 28 provinces (42).

The systematic approach in coaching and assistance of SMEs starting from awareness, approval, and commitment of business actors, understanding of standard management systems and technical product standards, gap analysis, system development, and implementation to continuous improvement, has had a positive impact on the business performances of SMEs. Business activities have become much improved in the organized production system, there has been an efficient use of resources, decreased rejects and errors, and the building of a better and more disciplined work culture. Several role model testimonials state that the benefits of implementing standards include maintaining sustainable quality, increasing efficiency, reducing revenue (reducing rejects), facilitating market access, reducing regular inspections cost in the production process, and also encouraging innovation.

SMEs are very diverse and generally use the potential of local resources, which are relatively available in district areas. The assistance of fostering SMEs in these areas includes access to information sources, market information, regulations, places for consultation and assistance, capital incentives, capacity building in online use, use of digital-based technology for marketing, and communication with partners. Zutshi et al. [9] give a systematic review and recommendations concerning enhancing SMEs' resilience in the context of COVID-19. To strengthen the SMEs, researchers can identify and assess the opportunities, interlinkages, and complexities associated with the use of digital technologies for SMEs. Moreover, to support the survivability of SMEs and their value-adding potential, the decision-makers can adopt the recommendations, while researchers and scholars may find it useful to test the viability of applying the proposed framework of recommendations onto SME settings. Digital marketing has been proved as helpful to SMEs in maintaining their sale performance during the COVID-19 pandemic while maintaining customers and sales performances in a sustainable manner, by improving customer satisfaction and building long-term relationships with customers [48,49].

The application of SNI is also able to expand their market access at the national level, in supermarkets, national retailers, e-catalogs, and marketplaces and some of the SMEs that are fostered are able to meet export market requirements (France, United States of America, Australia, Saudi Arabia, Middle East, South Korea, Singapore, and Timor Leste) [50].

In line with the government's program to encourage innovation, the development of standards must also be able to support the development of innovation. Creation of new products and processes have resulted from domestic research. Innovation must be supported in an integrated manner with standards and suitability assessment systems to improve the selling position of innovation products. Innovations that occur in the country are generally driven by community needs, developments in science and technology, and the global market. However, some innovations occur due to changes in community or market behavior. During the pandemic, there were many observations indicating that people's behavior had occurred as a result of this pandemic. Therefore, innovation and standard development support need to pay attention to this, so that the downstream process is getting better.

5. Conclusions and Recommendation

The COVID-19 pandemic has changed various aspects of life, not only regarding health aspects but also economic, social, and environmental aspects. Various government policies have been carried out, both directly related to health, or related to handling the impact of the pandemic. In line with ongoing and planned government policies, standardization including standard development, conformity assessment, and metrology play important roles in supporting health care. These roles start from supporting the handling of the pandemic, both related to medical equipment, personal protective equipment, competent laboratories, and reliable laboratory testing. Significant support of standardization for the government policies and programs can increase the effectiveness in strengthening the supply chain and fostering the SME. For recovery and continuing development post-pandemic, either in the middle- or long-term period will be more effective by implementation of a standard management system. This report is based on observations with selected cities that are representative of the Island of Java. Only two cities outside of Java were included, namely Makassar and Palembang. In future research, due to differences in demographics and conditions of infrastructure in various islands outside of Java, especially the eastern part of Indonesia, it is recommended to make a broader observation location to obtain comprehensive data in Indonesia. The methodology can be conducted in a more systematic manner to achieve better representative data.

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standards

Review

Overview of Standards Related to the Occupational Risk and Safety of Nanotechnologies

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Abstract: Nanomaterials offer new technical and commercial opportunities but, due to their low particle size, raise occupational health and safety concerns and may also pose risks to the consumers and the environment. In the last 15 years, many standards have been developed in the area of nanotechnologies, taking into account, namely, occupational risk and safety. This paper presents an overview of the standards in this area, with special emphasis at the ISO level, but also at European level, where standards are considered as an important support for legislation. A brief presentation of five relevant ISO standards is included. Relevant European Standards are also mentioned. The control banding approach for occupational risk management applied to engineered nanomaterials, according to ISO/TS 12901-2:2014, is presented. Standards are essential for society and should, in fact, be considered an important tool for companies to support sustainable products and process innovation.

Keywords: standards; nanotechnology; risk; health and safety

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1. Introduction

Nanotechnology has been promoted as the "next big thing" that will transform everyday life through the creation of numerous new products and enhanced materials for improved quality of life [1].

Although there are still few regulations regarding consumer products of nanomaterials, international organizations and the developed countries are trying to design guidelines and standards for toxicity evaluation and regulation plans, taking into account the nano-safety of humans and the environment. There is uncertainty on how nano-regulations may affect future funding, research, and development in the nano field, and this may lead to a delay in the commercialization of nanoproducts [2]. The regulations need the support of standards, namely in the areas of definitions, test methods, and specifications. There has been a strong increase in the development of standards in the area of nanotechnologies, especially since 2005.

According to National Nanotechnology Initiative (NNI), around the world, there are numerous standard-setting groups that are involved in developing nanotechnology standards. Some of the leading standard-setting organizations and their relevant nanotechnology committees are the International Standardization Organization (ISO) Technical Committee (TC) 229 on Nanotechnologies, ASTM International's Committee E56 (Nanotechnology) (formerly known as the American Society for Testing and Materials), the International Electrotechnical Commission Technical Committee 113 (Nanotechnology Standardization for Electrical and Electronics Products and Systems), and the Institute of Electrical and Electronics Engineers' Nanotechnology Council. These groups develop voluntary standards. Standards that are the best formulated, with the strongest basis in science, are most likely to be adopted by the global community. The U.S. also holds leadership of the ISO TC 229's Working Group 3: Health, Safety, and Environmental Aspects of Nanotechnologies, with a representative from The National Institute for Occupational Safety and Health (NIOSH) [3].

At the European level, the Technical Committee CEN/TC352—Nanotechnologies is linked to its international counterpart, ISO/TC 229—Nanotechnologies, and to the Committees in charge of nanotechnologies within the EU Member States' National Standardization Bodies. CEN/TC352 has four working groups, one of which, WG3, deals with health, safety, and environmental aspects.

Occupational Health and Safety aspects are considered as very important for the European Commission. Nanomaterials offer new technical and commercial opportunities but, due to their low particle size, raise occupational health and safety concerns and may also pose risks to the consumers and the environment [4–6]. The European definition of nanomaterials emphasizes the concerns about health and safety and is an important basis for all the legal requirements related to nanomaterials.

In this study, an overview of the standardization related to the Occupational Risk and Safety of Nanotechnology is presented.

The ISO standard describing the use of the control banding approach for occupational risk management applied to engineered nanomaterials has been used in a case study in a textile finishing company.

1.1. Overview of Nanotechnology in the World

This section is based on the information disclosed by the company StatNano, namely the "Standard Database" on standards and publications related to nanotechnology, with the status, level, year, organization, country, and classification.

According to StatNano, 1422 nanotechnology standards have been published by consensus and approved by 42 recognized bodies since 1992 [7]. Table 1 shows a conspicuous drop since 2019, when 368 standards were published, most of which were adopted.

Table 1. The number of published nanotechnology standards between 2018 and 2022 [7,8].

Year	Number of Published Standards
2018	237
2019	368
2020	339
2021	335

StatNano [8] recently presented a survey of nanotechnology publications in 2021. Table 2 presents the total number of nano-articles published in 2021 by the first 10 countries, as well as the share of the nanoparticle articles in relation to the total number of articles.

Table 2. Number of nanotechnology publications in 2021 per Country [9].

Ranking	Country	Total Number	Share of Nano-Articles to Total (%)
1	China	85,758	14.1
2	USA	23,225	4.5
3	India	19,041	13.9
4	Iran	11,196	18.7
5	South Korea	10,355	12.9
6	Germany	9019	6.1
7	Japan	7734	7.2
8	Saudi Arabia	6923	17.4
9	UK	6205	4.0
10	Russia	5888	10.2
	World	201,818	-

The relevance of China is very clear. Iran and Saudi Arabia appear in a relevant place, with a high share of nano-articles to total articles.

1.2. International Standards for Risk and Safety in Nanotechnology

The standard ISO 45001:2018—Occupational Health and Safety Management Systems presents very useful information on how to manage this topic in companies. It is aligned with ISO 9001:2015 and other management systems. Concerning nanotechnologies, the ISO has been developing a large set of standards, especially within the ISO Technical Committee 229, created in 2005. Up until now (December 2021), a total of 97 standard documents have been published, and 27 are under development [4].

Working group 3 of the ISO/TC229 deals specifically with Health, Safety, and Environmental Aspects of Nanotechnologies. The following five documents are especially relevant:

- ISO/TR 13121:2011. Nanotechnologies—Nanomaterial risk evaluation. ISO/TR 13121:2011 describes a process for identifying, evaluating, addressing, making decisions about, and communicating the potential risks of developing and using manufactured nanomaterials in order to protect the health and safety of the public, consumers, workers, and the environment. ISO/TR 13121:2011 offers guidance on the information needed to make sound risk evaluations and risk management decisions, as well as how to manage in the face of incomplete or uncertain information by using reasonable assumptions and appropriate risk management practices. Further, ISO/TR 13121:2011 includes methods to update assumptions, decisions, and practices as new information becomes available and on how to communicate information and decisions to stakeholders. ISO/TR 13121:2011 suggests methods that organizations can use to be transparent and accountable in how they manage nanomaterials. It describes a process of organizing, documenting, and communicating what information organizations have about nanomaterials [10,11].
- ISO/TS 12901-1:2012. Nanotechnologies—Occupational risk management applied to engineered nanomaterials—Part 1: Principles and approaches. ISO/TS 12901:2012 provides guidance on occupational health and safety measures relating to engineered nanomaterials, including the use of engineering controls and appropriate personal protective equipment, guidance on dealing with spills and accidental releases, and guidance on the appropriate handling of these materials during disposal. ISO/TS 12901-1:2012 is intended for use by competent personnel, such as health and safety managers, production managers, environmental managers, industrial/occupational hygienists, and others with responsibility for the safe operation of facilities engaged in the production, handling, processing, and disposal of engineered nanomaterials. ISO/TS 12901-1:2012 is applicable to engineered materials that consist of nano-objects such as nanoparticles, nanofibres, nanotubes, and nanowires, as well as aggregates and agglomerates of these materials (NOAA) [10,12].
- ISO/TR 13329:2012—Nanomaterials—Preparation of the material safety data sheet (MSDS). This document provides guidance on the development of content for, and consistency in, the communication of information on safety, health, and environmental matters in safety data sheets (SDS) for substances classified as manufactured nanomaterials and for chemical products containing manufactured nanomaterials. It provides supplemental guidance to ISO 11014:2009 (Safety data sheets for chemical products) on the preparation of SDSs generally, addressing the preparation of an SDS for both manufactured nanomaterials with materials and mixtures containing manufactured nanomaterials [4,13].
- ISO/TS 12901-2:2014. Nanotechnologies—Occupational risk management applied to engineered nanomaterials—Part 2: Use of the control banding approach. ISO/TS 12901-2:2014 describes the use of a control banding approach for controlling the risks associated with occupational exposures to nano-objects and their aggregates and agglomerates greater than 100 nm (NOAA), even if knowledge regarding their toxicity and quantitative exposure estimations is limited or lacking. The ultimate purpose of control banding is

to control exposure in order to prevent any possible adverse effects on workers' health. The control banding tool described here is specifically designed for inhalation control. Some guidance for skin and eye protection is given in ISO/TS 12901 1. ISO/TS 12901-2:2014 is focused on intentionally produced nano-objects, such as nanoparticles, nanopowders, nano fibres, nanotubes, and nanowires, as well as on aggregates and agglomerates of the same. As used in ISO/TS 12901-2:2014, the term NOAA applies to such components, whether in their original form or incorporated in materials or preparations from which they could be released during their lifecycle. ISO/TS 12901-2:2014 is intended to help businesses and others, including research organizations, engaged in the manufacturing, processing, or handling of NOAA, by providing an easy-to-understand, pragmatic approach for the control of occupational exposures [10,14].
- ISO/TR 12885:2018. Nanotechnologies—Health and safety practices in occupational settings. This document describes the health and safety practices in occupational settings relevant to nanotechnologies. This document focuses on the occupational manufacturing and use of manufactured nano-objects and their aggregates and agglomerates greater than 100 nm (NOAAs). It does not address health and safety issues or practices associated with NOAAs generated by natural processes, hot processes, and other standard operations which unintentionally generate NOAAs or potential consumer exposures or uses, although some of the information in this document can be relevant to those areas [10,15].

At the European level, the Technical Committee CEN TC 352 was created in 2006. Under AFNOR/UNMZ (France/Czech Republic) secretariats, the CEN/TC352 is engaged in standardization in the field of nanotechnologies. This includes the development of a set of standards addressing the following aspects of nanotechnologies: classification, terminology, and nomenclature; metrology and instrumentation, including specifications for reference materials; test methodologies; modelling and simulation; science-based health, safety, and environmental practices; nanotechnology products and processes [4].

Under CEN/TC 352 coordination, several CEN Technical Committees are involved in the execution of Mandate M/461 from the European Commission; several European standards have already been published under this Mandate, and several others are in preparation. Many of them have a relation with occupational health and safety.

At present (December 2021), 51 European standards have been published (32 out of these are EN/ISO documents, in conjunction with ISO/TC229), and six are under preparation. The updated list is available online: https://standards.cen.eu/ (accessed on 15 December 2021).

It is also worth mentioning the standards developed within the European Technical Committee CEN/TC 137—Assessment of workplace exposure to chemical and biological agents. The following eight standard documents are in the area of nanotechnology:

- EN ISO 28439:2011—Workplace atmospheres—Characterization of ultrafine aerosols/nanoaerosols—Determination of the size distribution and number concentration using differential electrical mobility analyzing systems (ISO 28439:2011)
- EN 17058:2018—Workplace exposure—Assessment of exposure by inhalation of nano-objects and their aggregates and agglomerates
- EN 16966:2018—Workplace exposure—Measurement of exposure by inhalation of nano-objects and their aggregates and agglomerates—Metrics to be used such as number concentration, surface area concentration, and mass concentration
- EN 16897:2017—Workplace exposure—Characterization of ultrafine aerosols/nanoaero sols—Determination of the number concentration using condensation particle counters
- CEN ISO/TS 21623:2018—Workplace exposure—Assessment of dermal exposure to nano-objects and their aggregates and agglomerates (NOAA) (ISO/TS 21623:2017)

In 2006, the OECD (Organization for Economic Co-operation and Development) established the Working Party on Manufactured Nanomaterials (WPMN) as a subsidiary body of the OECD Chemicals Committee. This program concentrates on human health and environmental safety implications of manufactured nanomaterials. Since then, OECD has published more than 100 guidance documents under the series of Safety of Manufactured Nanomaterials [4]. The SOP (Standard Operating Procedures) developed by OECD have been supported at the international level and, therefore, can be used for regulatory purposes.

The full list of all the freely downloadable documents can be consulted at http://www.oecd.org/env/ehs/nanosafety/publications-series-safety-manufactured-nanomaterials.htm (accessed on 15 December 2021).

Note that three of the documents published by the OECD in November 2021 are very relevant: "Evaluation of Tools and Models for Assessing Occupational and Consumer Exposure to Manufactured Nanomaterials" (in 3 parts).

It is important to emphasize the so-called "Malta Initiative" (which arose during the Maltese EU Council Presidency in 2017), involving 18 European countries, in which several Directorate-Generals of the European Commission, the European Chemicals Agency (ECHA), authorities, research institutions, NGOs, universities, and industry work joined together on a voluntary and self-organized basis. The aim of this initiative is to make legislation enforceable, in particular in the chemicals sector. For this purpose, it is necessary to ensure that the essential test, measurement, and verification procedures are available. Currently, the work is focused on amending the OECD Test Guidelines in the area of nanomaterials to ensure that a nanomaterial-adapted REACH Regulation will become enforceable [4].

2. Control Banding Approach in Occupational Risk Management Applied to Engineered Nanomaterials

Nanomaterials constitute a new generation of toxic chemicals. As particle size decreases, in many nanomaterials, the production of free radicals increases, as does toxicity [16]. The number of commercial products and the number of workers potentially exposed to engineered nano-materials is growing, as is the need to evaluate and manage the potential health risks [17]. The control banding approach for occupational risk management applied to engineered nanomaterials, according to ISO/TS 12901-2:2014, is a pragmatic approach useful for the control of workplace exposure to possibly hazardous agents with unknown or uncertain toxicological properties and for which quantitative exposure estimations are lacking [4].

The Control Banding process, according to ISO/TS 12901-2:2014, includes the following elements:

- Information gathering;
- Assignment of the nano-objects to a hazard band (on the basis of a comprehensive evaluation of all available data on each material, taking into account parameters such as toxicity; in vivo biopersistence; and factors influencing the ability of particles to reach the respiratory tract, their ability to deposit in various regions of the respiratory tract, and their ability to elicit biological responses);
- Description of potential exposure characteristics (assigning an exposure scenario at a workplace to an exposure band, taking into account the physical form and amount of the nano-object, dust generation potential of processes, and actual exposure measurement data);
- Definition of recommended work environments and handling practices (control banding);
- Evaluation of the control strategy or risk banding.

This standard has been applied in several studies, for instance, in an interesting study that evaluated workers' exposure to nano-objects in R&D laboratories by means of the control banding technique [18].

The authors also applied this methodology in a case study in a textile finishing company involving two chemical finishes containing nanomaterials: a mosquito repellent and antibacterial finish. The risk analysis mainly concerned four workers involved either in the preparation of the finishing baths or on the conducting of the stenter frame. Hazard bands and exposure bands were evaluated, according to ISO/TS 12901-2:2014. Following the application of this standard, the control bands corresponding to the exposure of the different workers to the nanomaterials were established. As a result, the following measures to mitigate risks were envisaged: appropriate ventilation and use of adequate personal protective equipment. Hazards related to one of the chemicals were higher and also required the use of a closed booth and a smoke extractor [6].

There is now a specific REACH registration system for nanomaterials, which came into force from January 2020 (Commission Regulation (EU) 2018/1881 of 3 December 2018), so it is recommended that the suppliers of chemicals which incorporate nanomaterials include more information on the hazards and measures for risk mitigation in the safety data sheets, based, for instance, on the recommendations presented in ISO/TR 13329. This information is essential for implementing the control banding approach [4].

The new Commission Regulation (EU) 2020/878 of 18 June 2020, amending Annex II to REACH, presents more detailed requirements to be included in the safety data sheets of chemicals that contain nanoforms. This Regulation applies from 1 January 2021, with a transitional period until 31 December 2022 [4].

3. Conclusions

This study has presented an overview of the standard documents related to Safety and Risk relevant for Nanotechnologies. The most relevant activities at the international level are related to ISO/TC229. Five standard documents developed within the ISO have been highlighted, and a case study applying one of them has been presented.

At European level, it was suggested to follow the activities of the European Agency for Safety and Health at Work (EU-OSHA). The website of EU-OSHA is the best place to follow all the relevant EU legislation, with links to legislation at the national level, supported by standards.

The increasing concerns related to the health and safety of nanomaterials are leading to the emergence of standards. It is essential that all stakeholders keep aware of all the updated legal requirements and standard documents, considering these not only as limitations, but also as opportunities for improvement.

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Review

Quality and Historical Marks of National Interest: The Italian Case Study

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Abstract: Trademarks are distinctive signs designed to promote and enhance the products/services of companies. In recent years, the concept of quality has asserted growing interest, especially among enterprises, aiming to promote consumers by creating distinctive marks. In Italy, in 2021, the number of filled quality trademarks for products and services will amount to about 81. Through the "Decreto Crescita", Italy supported Italian companies to limit their delocalization overseas. In this regard, the historical mark of national interest was established, from which Italian companies with a trademark filed for at least 50 years can benefit. Therefore, the study aimed at evaluating two different types of trademarks, quality marks and historical marks, highlighting the main aspects that characterize these two marks as a function of the standards that distinguish them from the most common trademarks. For this purpose, the study focused on evaluating historical brands in Italy to promote their strategic importance and enhance the temporal continuity of the marks. These were considered a new marketing tool to promote know-how and "Made in Italy", which is particularly useful for the brand image of companies to be competitive in a global market.

Keywords: quality trademarks; standardization; historical trademarks; service; products; Italy

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1. Introduction

Customers' choice of goods and services is often influenced by visual recognition and the memory of trademarks [1]. They are an essential part of everyday life as they shape people's choices and attitudes and predispose them to consumption [2,3]. According to Regulation (EU) 2017/1001 [4], trademarks represent all those signs such as words, names of persons, designs, letters, numerals, colors, packaging and sounds, which are suitable to distinguish the goods or services of a company from those of other enterprises, and they could be considered as a tool for guaranteeing and recognizing the quality of a company, alternative but potentially complementary to certification [5]. They allow consumers to differentiate the products/services from others on the market, and they are placed at the base of the communication strategies of companies for the choice of products by consumers.

According to Reg. 2017/1001, the trademark should:

- Have distinctive skills: it cannot be limited to words that clarify only the type of activity carried out or product;
- Be lawful: it cannot be contrary to public order and must not violate the provisions of the law.
- Different trademark protection systems can be distinguished:
- International trademarks, administered by the World Intellectual Property Organization (WIPO), confer protection in different countries through the Madrid Convention and its Additional Protocol [6];
- European Union trademarks, which have general effect in all EU Countries, which do not replace national trademark systems but constitute a parallel and additional legal framework in the territory of the EU Member States [7];

– National trademarks, registered by the Intellectual Property Offices of the Member States (Ufficio Italiano Brevetti e Marchi—UIBM, for Italy) based on a harmonized system at EU level [7].

In recent years, brands are no longer considered only as marketing tools but also as means that allow achieving relevant social results, such as promoting healthy life, sustainable behaviors for the environment, ethically correct choices aimed at safeguarding workers, and more. Therefore, brands play a vital role for the consumer, representing the possibility of creating a bond of relationship and trust, through repeated consumption, between the consumer and the company that owns the brand [3]. Indeed, this link between the consumer and brand can influence the company performance holding the brand [2–4]. In this regard, it is essential to highlight how the "customer experience" is one of the main factors in strong brands development (brands that have strong originality and a remarkable distinctive capacity) and how brand coverage from a media point of view can influence individual choices and preferences [8].

In this regard, the concept of "brand equity" was born, that is, the added value that a particular brand gives to the products/services of a company [9]. Therefore, the representation of goods/services through brands acts as a differential element that helps the consumer's decision-making based on personal experiences. Therefore, all those brands that present and confer high brand equity can allow for better profit margins, consequently improving communication with the consumer and therefore playing a significant role in the consumer's choices and increasing the credibility of the company associated with that brand [10]. Furthermore, brands with high brand equity can present improved future profits, induce customers to pay higher prices, and increase brand visibility in the market. Therefore, brands are strategically important because they allow companies to communicate their value to the consumer and become a benchmark within their industry. It is possible to distinguish between quality marks (QMs) and historical marks (HMs) in this context. The former is used to certify the value of raw materials and production and processing methods of certain products [11].

The importance of QMs refers to the protection of the consumer, who is more aware of the product's characteristics, and the producer, who sees his work recognized through an official certification. In contrast, the latter is used to recognize the protection of products or services made by a productive national enterprise of excellence historically linked to a specific territory [12]. In this way, products acquire added value compared to conventional ones, entering a different market niche characterized by quality and higher prices. The strategic importance of HMs concerns being a lever for a country's competitiveness and internationalization. Hence, the study aims to analyze the difference between QMs and HMs, highlighting the main aspects that characterize these two brands as a regulation function and the specifications that distinguish them from the most common trademarks. In particular, a case study focusing on the historical trademarks in Italy was proposed to promote the strategic importance of marks, thus enhancing them as a driver of competitiveness and internationalization.

2. Trademarks in Europe

The Treaty on the Functioning of the European Union [13] provides that in order to establish and operate the internal market, standard measures shall be established among the 27 Member States of the European Union in order to ensure uniform protection of intellectual property rights in the Union and for the setting up of centralized authorization, coordination and control systems at Union level. Regulation (EU) 2424/2015 [14], repealing Council Regulation (EC) 207/2009 [15], created a specific trademark protection system for the European Union, which operates in parallel with the trademark protection available at the level of individual member states following their respective national protection systems.

Regulation (EU) 2424/2015 provides the following definition of a European Union trademark: "all signs, such as words, including names of persons or designs, letters, numerals, colors, the shape of goods or their packaging, and sounds, provided that such signs are suitable for: (i) distinguish the goods or services of one undertaking from those of other undertakings; (ii) be represented in the EU register of trademarks in such a way as to enable the competent authorities and the public to determine clearly and precisely the subject matter of the protection granted to their proprietor" (Art. 4 reg. 2424/2015).

Regulation (EU) 2424/2015 and Directive (EU) 2015/2436 [16] constitute the "trademark package". These are the two parts of reference legislation aimed at harmonizing the Member States' trademark laws with each other, but also to make the national laws and that part of European regulation that directly controls the "European Union trademark", that is, the industrial property title issued by the European Intellectual Property Office (EUIPO) that is in effect in all Member States.

In Europe, the number of trademarks registered in 2021 was approximately 15 million [17]. The countries with the highest number of brands are France (5.7 million), followed by Germany (4.9), Italy (3.7) and Spain (3.5) (Figure 1) [18]. Of these, 51.91% are words, while the remainder are combination marks (words/figure) (24.86%), figures (17.32%) and others (5.51%) (Figure 2) [18].

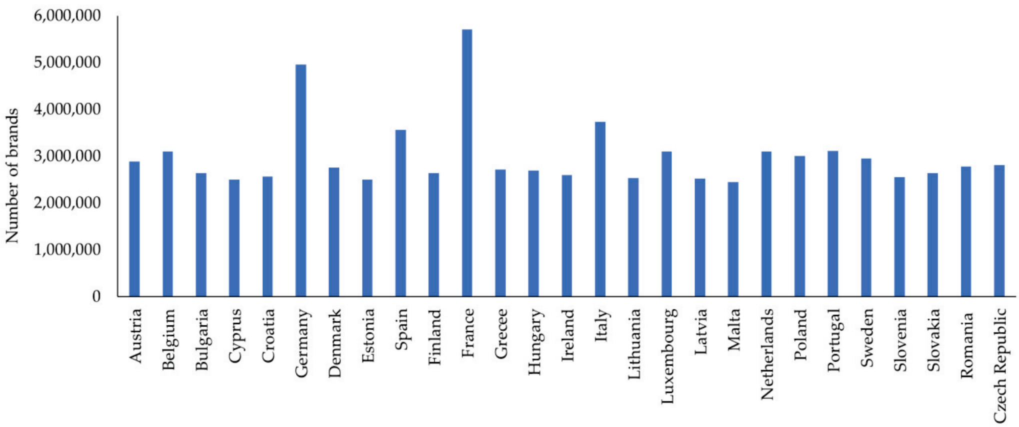

Figure 1. Number of the brand in 27 Member Countries of the EU [18].

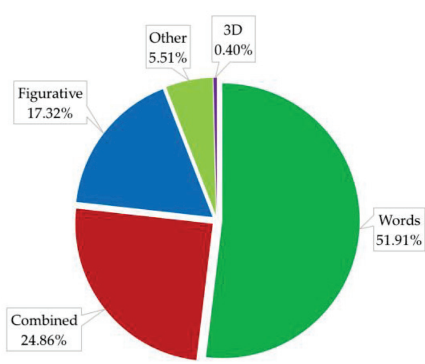

Figure 2. Different types of trademarks in the EU [18].

Figure 3 [18] shows the trademarks registered in the EU divided according to the Nice Classification [19], which divides them into product and service marks. Product trademarks are in turn subdivided into 34 classes according to the nature of the product in question, and service marks are subdivided into 11 subclasses, thus making it possible to classify directly or by analogy most products and services.

Figure 3. Number of produce and service brands in Europe in 2021 [18].

The most widely registered product brands are in the agri-food sector (11.5 million), scientific instruments (2.5 million), paper and cardboard (1.7 million), clothing (1.6 million), pharmaceuticals (1.4 million) and cosmetics (1.1 million). As far as service brands are concerned, those in the training sector (2.6 million), advertising (3.2 million) and scientific research (2.2 million) are those most represented. Of these brands, only 52.09% are registered, the remaining percentage being represented by 34.04% of expired brands, 10.36% of ended brands and 2.7% of filled brands [18].

2.1. Quality Marks in the EU

QMs, compared to individual and collective marks, whose differences are expressed in Table 1, are different not only in terms of function but also in some more formal aspects. EU quality policy aims to protect the names of specific products in promoting their unique characteristics related to geographical origin and traditional skills. Therefore, QMs are tools for recognizing the added value of a specific product in terms of its origin and-or production methods, generally linked to a local tradition or territoriality [20,21]. In the EU, QMs have been defined in the first instance by Directive 2006/123/EC [22] as those marks whose function is to certify whether the product/service on which the brand is affixed has specific quality characteristics and/or follows certain ethical, environmental, etc. standards. Therefore, this brand indicates that the good or service has achieved specific quality standards set by the certifying body.

Table 1. Differences between individual, collective and certification marks.

Individual Brand	Collective Brand	Certification Brand
It has the function of distinguishing the production or marketing of products and services by bringing them back to one entrepreneur rather than another.	It indicates that the protected goods or services come from members of an association and can only be used by the latter.	It is an indication that the goods or services meet specific characteristics (e.g., qualities) defined in the regulations of use.
A natural person or a company can register it. It will also be that person or company to use the trademark and have exclusive rights.	Only associations of manufacturers, producers, service providers or traders, and legal persons under public law (if they have an organization like that of associations) may file a collective mark application.	The holder of a certification mark may not manage an activity involving the supply of goods and services of the certified type (neutrality requirement).
It cannot describe a product's characteristics or indicate its geographical origin because it is information about the product that a single company cannot monopolize.	The application must include the rules of use.	Natural persons may also apply for a certification mark.
-	-	The application must include the rules of use.

A QM refers to the assurance of specific characteristics of certain products and services. One crucial difference is that the holder of a certification mark (a natural or legal person, an institution or authority, and bodies governed by public law) may not operate an activity involving providing products and services of the certified type [23]. The holder of a QM may certify the products and services that others use in their respective activities but may not certify his products and services and use certification himself. He has an obligation of neutrality about the interests of the manufacturers of the products or providers of the services he certifies [24]. A quality mark can be defined by four aspects [25]:

- It must be a sign likely to be represented in the EU trademark register. In addition, such a sign should distinguish goods and services that are certified from others that are not.
- When submitting a QM application, the type of mark for which the application is made should be indicated very clearly.
- The QM application must relate to the goods and services certified by the trademark owner.
- It must include the regulations for using the QM for which the application is made.

The use regulation constitutes the essence of the QM. Table 2 shows the mandatory contents that QM "regulations use" must have (17 of Implementing Regulation (EU) 2018/626) [26]. The EU Regulations define that QMs must be filed within two months of application and contain:

- The declaration that the applicant is not carrying out any activity involving the certified type's supply of products or services.
- The characteristics of the products or services to be certified.
- The conditions of use of the EU certification mark.
- The holder of the MFF applies the verification and monitoring arrangements.

Table 2. Mandatory information to be reported in the regulation of the use of quality marks in the EU [20,26].

Mandatory Information	Description
Name of the applicant	The applicant's name must be the same as that in the application for the trademark registration
The declaration that the applicant does not carry out any activity involving the supply of products or services that must be certified with the QM.	The following particulars shall be given: "I hereby declare that I am not carrying out any activity involving the supply of [products] [services] [products and services] subject to certification". "[Name of applicant] declares that it fulfils the conditions laid down in Article 83(2) of Regulation (EU) 2017/1001 of the European Parliament and of the Council of June 14 2017, on the European Union trademark."
Representation of QM	The representation of the mark must be the same as that shown in the application.
The products or services covered by the QM.	The list of goods and/or services is the same as that provided in the application, referring to the EU community application number.
The characteristics of the products or services to be QM certified (like the material, the manufacturing process of the products or the provision of services, quality or precision).	The description of the characteristics of the applicant is certifying can be provided using general terms, without indicating in detail all aspects and all technical specifications. The characteristics must be specified and explained clearly, being necessary to allow the target public to understand them clearly and precisely: – Suppose the specification concerns a series of products and services, with different characteristics to be certified, depending on the individual products/services category. In that case, the characteristics to be certified must be specified for each of the different types of products. – About services, their characteristics must be specified for each of the different types of services and not the characteristics of the service providers.
The conditions of use of the EU certification mark, including penalties.	– It is necessary to include the specific conditions of use imposed on the authorized user: that the mark must be used as an EU certification mark; if there are taxes to be paid in connection with the use of the trademark; etc. – The use and conditions of use must refer to the representation of the required sign. – It is mandatory to specify the appropriate penalties if the conditions of use are not respected.
Persons authorized to use the QM.	– A clear indication of who has the right to use the trademark – If the applicant intends to list the authorized QM users, it may utilize a link to a website, allowing them to be systematically updated without the need to amend this regulation. – Persons authorized to use QMs must be referred to as "authorized users". The latter do not have the right to transfer or license the use of the QM to third parties.
The procedures for verifying the characteristics and monitoring the use of the QMs by the certification body.	– It is necessary to specify the verification procedures adopted and the surveillance system used by the applicant/holder of the MFF to ensure that the goods and-or services covered by the trademark possess the certified characteristics. – The applicant does not necessarily have to carry out the checks. – The verification of the goods and services covered by the trademark and the monitoring of the conditions of use may be limited to random or random checks and should not be extended to all certified products or users.

Geographical Indications (GIs)

In the field of QMs, to protect the great variety of European agri-food products, in 1992 the EU introduced a system of quality certification based on a geographical indication. This system protects the denominations of products from certain regions that have specific qualities or enjoy a reputation linked to the production area. It was created to defend some agri-food products that, when they cross the borders outside Europe, have to face the unfair competition of products having the same quality and characteristics, and in some cases even the same name. In this case, the counterfeiting of typical products, on the one hand, might be detrimental to local producers, and on the other hand, it could confuse consumers whom poor copies of original products would mislead. Therefore, GIs recognitions have a double purpose: for producers, to help them better market their products, and for consumers, to distinguish quality products. For an agri-food product to be designated as PDO, its whole production process must be carried out in a specific production area. In detail, geographical indications, as defined by Regulation 510/06/EC [27], include Protected Designation of Origin (PDO), Protected Geographical Indication (PGI) and the Traditional Specialties Guaranteed (TSG), whose principal differences are expressed in Table 3. In contrast, PGI certification is less restrictive, for example in the area of indication of typicality, it is enough to have even one production phase (usually the one which characterizes the product the most). On the other hand, STG does not protect the origin and/or area of the production process but its traditionality. At a global level, GIs products are about 1500. Italy is the country which has the most, 309 (of which 171 PDO, 135 PGI, 3 TSG), 21% of the total. It is followed by France (256), Spain (202), Portugal (140) and Greece (113) [28].

Table 3. GIs: main characteristics and differences.

Geographical Indications	Regulation	Focus
Protected Designed Origin (PDO)	REG. 510/06/EC [27]	It is a QM awarded by the EU to those agri-food products whose peculiar quality characteristics are strictly interdependent from the geographical area where the whole production process occurs. Therefore, it is a very restrictive mark of origin that requires that the whole process (production, processing and transformation) be carried out within a well-defined geographical area according to specific rules by law. Thus, the quality or characteristics of the agri-food product are exclusively determined by a particular geographical environment, including natural, human and climatic factors.
Protected Geographical Indication (PGI)		The EU attributes the QM of origin to all those food products for which a certain quality, reputation or other characteristics depend on the geographical origin. It is a little less restrictive than PDO, and it differs from it because it is enough that only one phase of the production process takes place within a specific geographical area (usually the phase that most characterizes the product).
Traditional Specialty Guaranteed (TSG)		It is a European trademark that protects at the community level the agri-food productions, not referring to the origin but the specificity and-or traditionality. By traditionality, we mean a food product that has been produced in the same way for at least 25 years. TSG aims to enhance the composition or the methodology used and not the product's origin. Therefore, it is addressed to those agri-food products having a specificity, in terms of production method rather than composition, specificity linked to the tradition of an area, and therefore production in that area is not necessarily required.

3. Trademarks in Italy

Italy ranks among the top three European countries with the highest number of registered trademarks [17]. In recent years there has been an increase in the number of applications for trademark registration (Figure 4).

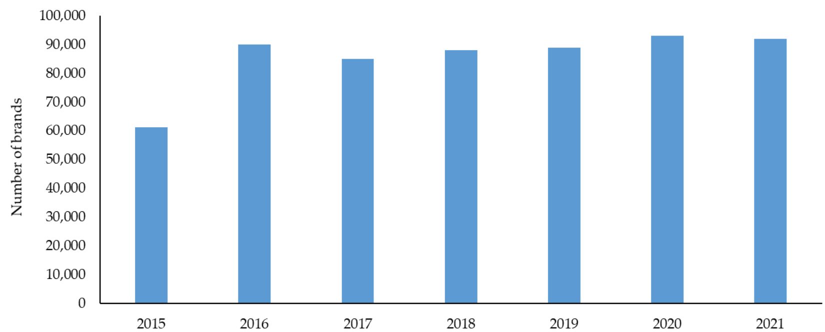

Figure 4. The number of trademarks registered in Italy from 2015 to 2021 (ongoing) [18].

Figure 5 shows the trademarks registered for the various classes of goods and services defined by the Nice Classification.

Figure 5. Number of trademarks registered in Italy according to the Nice Classification [18].

The product trademarks most frequently represented are those relating to clothing (44.3 thousand), scientific instruments (27.6 thousand) and foodstuffs (27.4 thousand). As far as service trademarks are concerned, those relating to training (56.3 thousand), the advertising sector (52.7 thousand) and agri-food services (27.5 thousand) are more represented.

3.1. Quality Trademarks in Italy

In Italy, the regulation of the collective trademarks is contained in Art. 11 of "Codice Proprietà Industriale (CDI)", as indicated by Legislative Decree 15/2019 [29]. Before the last reform, the collective mark had the function of guaranteeing compliance with quality standards or geographical origin by the marked products or services. Now, this function has partly shifted to the certification mark. In addition, today the function of the collective trademark is to specify the commercial origin of certain products/services by informing the consumer that the manufacturer of the products/services provider belongs to a specific association and has the right to use the trademark [20]. In order to obtain the registration of a collective trademark, whether European or Italian, it is necessary to file a regulation, which standardizes the conditions of membership in the association and, only eventually, the conditions of use of the trademark. The regulations may impose certain limitations on the trademark users, such as the location of the trademark, the size, the advertising methods, and more [30]. If the trademark describes the geographical origin of a product/service, the regulation must provide that all companies belonging to the same geographical area may participate in the association [29]. In Italy, the certification mark, in which QMs fall, is regulated in Art. 11 bis CDI, introduced by Legislative Decree 15/2019, in which the owner of the mark, or the certifying entity, decides whether the products/services of a company can use the mark. In any case, the owner is bound by an obligation of impartiality and may not use the mark for its own products/services or have interests in the sector in which the certification operates [29]. To harmonize the QMs registration procedure in Italy, in addition to the application for registration of the trademark, a form must also be submitted describing, in detail, the characteristics of this brand (Table 4).

Table 4. Quality Marks Characteristic Sheet.

Mandatory Information	Description
Character	A general trademark, i.e., covers all services in each province (and may also cover products), or a sectoral trademark, i.e., one or more service sectors (e.g., real estate).
Extension	This section refers to the geographical scope of the brand, which can be national or territorial (e.g., on a provincial basis).
Contents	The aim is to clarify whether the label is intended to guarantee quality in a general sense or to concern specific aspects (e.g., adherence to a code of conduct, safety, environment, social responsibility, etc.). Several characteristics can coexist in the same brand.
Purpose	The specific purposes of the trademark must be indicated.
Management	It is necessary to indicate the subject managing the mark, specifying whether it uses an external verifier, and whether or not it is an accredited certification body according to European Regulation 765/2008 [31].
Website	The link to the website of the managing entity is given
Referring Services	The reference sector(s) should be indicated. The ATECO classification [32] should be added to the sectors if available. If the trademark is deposited at the UIBM, according to the categories relating to Trademarks.
Filing of the trademark c/o UIBM	If the trademark has been filed with UIBM, the number and date of the registration certificate are shown. If the proceedings are still in progress, the date the application was filed is reported.
Member companies (optional)	It may indicate the number of undertakings belonging to a specific date.

In Italy, there are 81 quality brands; mainly, these trademarks refer to the application by products/services of quality standards (64%). In addition to the concept of quality, these brands are applied to respect and safeguard the environment (48%), promote local products (41%), adhere to conduct codes (19%), safeguard safety and human health (16%) and others

(11%) [33]. Often, these brands are characterized by the possibility of dealing with several aspects at once (Figure 6).

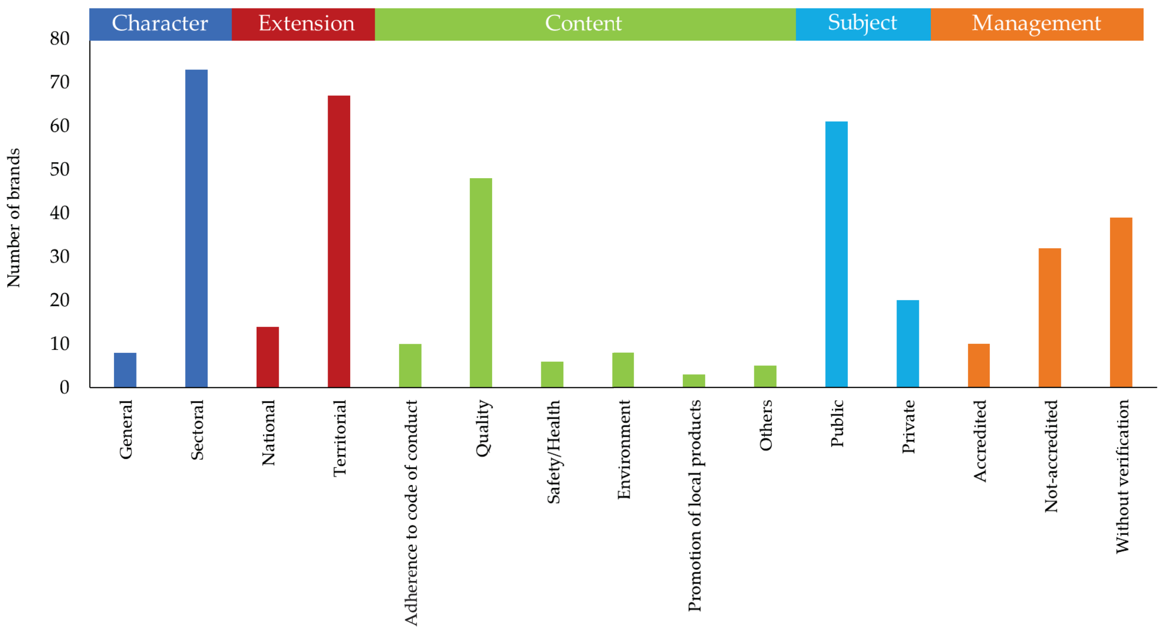

Figure 6. Number of brands according to the mandatory characteristics to be reported in the submission form for registration of quality marks [33].

Of these brands, 17% are applied nationally, while the remainder are applied on a territorial level with specific reference to a specific territory or province. These quality marks can be applied to a product/service following verification by public and private entities that guarantee compliance with the specific requirements of each quality mark defined in Table 4 and manage their use. In total, 75% of QMs are managed by public bodies, while private bodies manage 25%. In Italy, 48% of QMs do not require verification of the application of quality standards, while 40% are verified by non-accredited bodies and the remainder by accredited bodies (12%) [33]. In addition, 89% of Italian QMs are applied to specific sectors of interest (Figure 7).

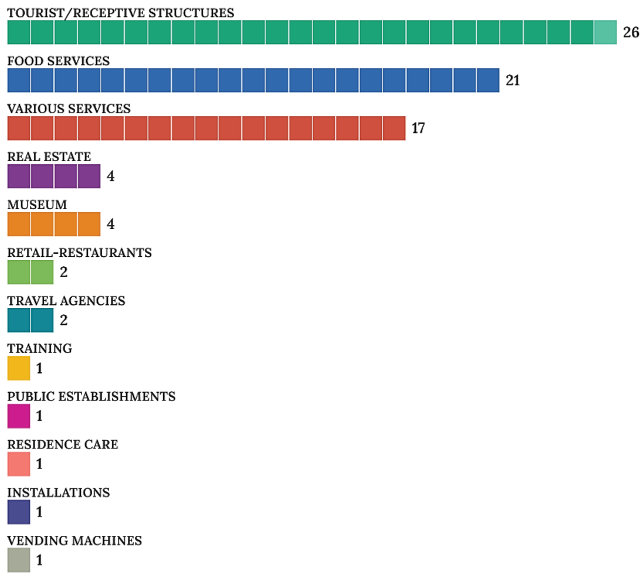

Figure 7. Quality trademarks by sectors.

3.2. Historical Trademarks in Italy

In 2019, Italy adopted measures to strengthen the protection of Italian brands, promoting the quality and historicity of their productions by establishing the concept of the historical mark. The desire to protect historical trademarks comes after what has been done in other EU Countries, such as Spain, Germany and France, and is regulated by Legislative Decree N. 30/2019 [34]. It is also called "Decreto Crescita". It has been provided that the owners or exclusive licensees of respective trademarks registered for at least fifty years or for which it is possible to demonstrate the continuous use for at least fifty years, used for the commercialization of products/services made in a productive national enterprise, can obtain the registration of the trademark in the register of historical trademarks of national interest. The Decreto Crescita is to support Italian industry by limiting the delocalization of production abroad and thus promote "Made in Italy", protecting the economic and social fabric that revolves around Italian companies. Regarding the concept of Made in Italy, based on EC Regulation 04/2008 n.450 [35], it is not only attributed to goods produced in Italy, but also to those that "the production of which two or more Countries or territories have contributed and which have undergone the last substantial transformation in Italy". In this context, many foreign-made products of low quality are started elsewhere and finished in Italy, adding the Made in Italy mark on the label, exploiting the excellent reputation of Italian manufacturing sectors. Due to the misleading use of products made abroad, of names, brands, signs, references, images, and colors that evoke Italy, it is called "Italian Sounding". In order to fight this phenomenon, Art. 32 of the Decreto Crescita establishes a tax credit equal to 50% of the expenses incurred for the legal protection of Italian products, including agri-food products, to support Italian companies in the fight against this unpleasant industrial phenomenon. The protection of Made in Italy is closely linked to the territoriality and the Italian character of particular productions. Historical Italian brands have become prey to foreign buyers, who, once they have obtained the ownership of the brand, have moved the production abroad, closing the production plants in Italy, thus cancelling the Italian character of the products marked by a specific brand, impacting the wealth of the Country, with relevant consequences on the employment level.

In this context, therefore, to safeguard employment levels and the continuation of production on the national territory, the need has arisen to establish a register for the protection of historical brands.

The application for registration of Italian historical trademarks should contain:

- The complete data of the company applying for registration and its status.
- Details of the first registration and subsequent renewals if the trademark is filled.
- If the trademark is not filed, documentation showing the actual and continuous use of the trademark for at least 50 years specifying the goods (or services) to which it relates. If there is a need to prove the actual use of a trademark, the application for registration is represented by the same documentation.
- A substitute declaration stating that the trademark for which registration is requested is used for the products' marketing (or for the provision of services) of a national company of excellence historically linked to the national territory.

This Decree does not constitute a new title of industrial property, but rather the historical trademark represents a recognition made to all those companies that are owners or exclusive licensees of a trademark that has been used for over 50 years. Historical trademark guarantees merely the entrepreneurial origin of the goods and services for which it is registered and used, that is, the fact that a particular person has exclusive rights (and responsibility) for those goods and services for which the trademark is used. The ability of a company to survive for many years in an increasingly complex and constantly evolving market is often indicative of solid structure, production capacity and know-how, which therefore deserve to have a concrete recognition for what has been done over the years, also in terms of impact on local communities. Therefore, the owners of trademarks with these characteristics will register their rights on the new register of historical trademarks of national interest.

As a result of the Decreto Crescita in 2020, the "Historical Trademark of National Interest" logo was established, which the companies listed in the register can use for commercial and promotional purposes. This logo, which consists of an image of Italy with the words "Marchio Storico" written around it, may be used alongside the trademark only with the products/services for which the trademark is registered. The advantage of being registered in this register is the possibility of benefiting from the "Fondo per la tutela dei Marchi Storici", that is, funding aimed at the economic enhancement of historical trademarks of national interest by small-medium enterprises which own or exclusively license the Historical Trademark [34].

The purpose of the Historical Trademark institution is to protect historic Italian companies' industrial property by promoting national companies that have been operating in the territory for over half a century. In this way, the Italian Government has set itself up as the guarantor of Italy's industrial history, linking the historical brands and therefore the company holding them to the national territory. Currently, the registered Historical Trademarks are equal to 267. The trademarks representing the first three sectors reflect the leading sectors of the Italian economy. Among these, the most represented sector is the food industry, which holds 33% of the total historical brands, followed by beverages (13%) and the fashion and textile sector (8%) [36]. Figure 8 shows historical marks by sector.

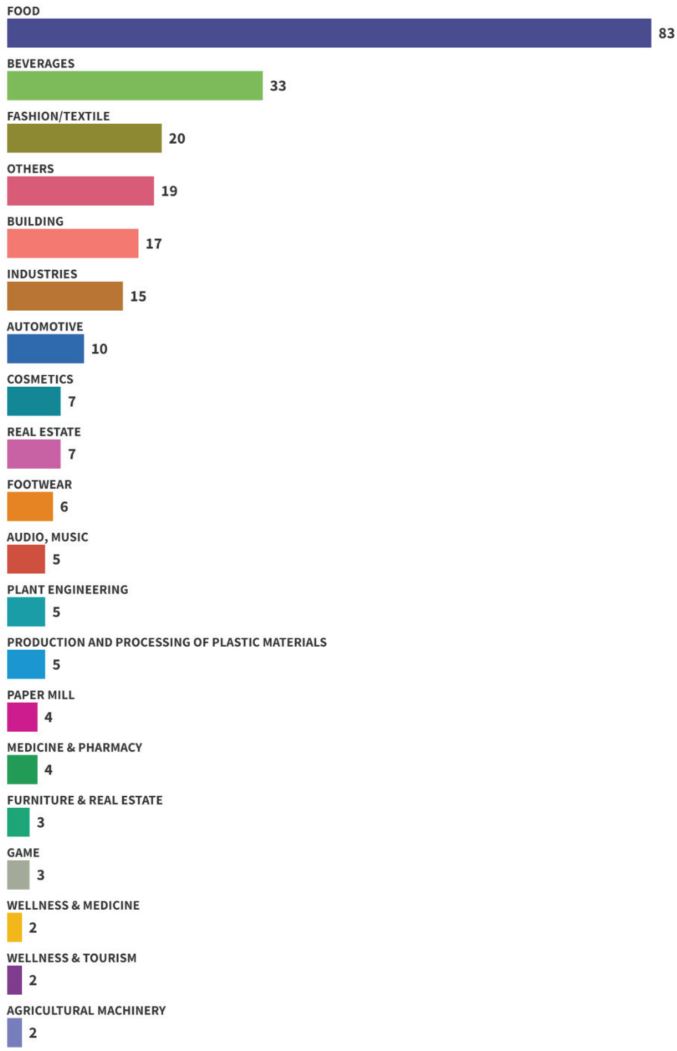

Figure 8. Historical trademarks classified by application sectors.

4. Conclusions

Trademarks are distinctive symbols of products and services and have always been a reference point for consumers' purchasing decisions. In addition, trademarks guarantee quality for consumers and protection for the producer against fraudulent copying of their products or use of their trademark. In this regard, the study evaluates the standards of application of two different trademarks, quality trademarks and historical trademarks, focusing on their diffusion in Italy. Quality marks are an alternative but, at the same time, complementary guarantee instrument to certification. Among quality marks, historical marks play a crucial role in evaluating the temporal continuity of the corporate identity, as it is assessed in its "historicity". The registration in the historic trademark register is a guarantee of know-how related to the specific sector of the trademark and, at the same time, is perceived as an attribute of quality and "Made in Italy".

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Article

Evaluating Management Practices in Precision Agriculture for Maize Yield with Spatial Econometrics

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Abstract: Precision agriculture (PA) aims to provide data on soil, nutrient use, irrigation, and crops, to guide management strategic decisions towards an efficient use of inputs, increasing production and avoiding environmental problems due to excessive accumulation of fertilizers. In this paper, PA data from a large Portuguese farm producing maize were used to assess the effectiveness of agronomic management decisions concerning fertilizer and nutrient use, seed choice, and water content, in terms of crop productivity. The maize yield in 2017 and 2018 was modelled as a function of manageable inputs and unmanageable factors introduced as control variables. Panel spatial econometric methods were used for specification and estimation, to control for spatial dependence and spatial heterogeneity. The model proved to fit the data remarkably well and could be a good reference for specifying models to explain maize production; thus, helping researchers who need to deal with the huge amount of data that normally originates from PA. Additionally, it can be considered another tool for farm managers, helping in the design and evaluation of their agronomic management decisions.

Keywords: precision agriculture; agronomic management; maize yield; spatial panels; spatial regression models

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1. Introduction

Precision agriculture (PA) emerged as a concept in 1997 (see [1]); consisting in the gathering of large amounts of data based on information technologies, in order to guide site-specific agronomic management concerning crop production, to provide benefits in crop quality, profitability, productivity, sustainability, and environmental protection. Since 1997, the techniques used by PA have evolved considerably, with the consequent availability of more and diverse data: see [2] for a review on the way remote sensing technology can be used as an effective tool in PA; and more recently [3], analyzing how recent technologies such as geospatial technologies, internet of things, big data analysis, and artificial intelligence can be useful in guiding agronomic management decisions to improve crop productivity.

The present paper focuses on the assessment of agronomic management decisions in PA, rather than the technological aspects of data gathering or the agronomic and environmental issues related to PA, in the sense that it concerns the use of quantitative methods to allow farmers to assess the efficacity of their management decisions concerning crop inputs. In this line, and following [4], a remark is needed to warn against the error of confounding the value of precision technology, itself, with the information usefulness when using PA technology. This paper is concerned with the former, that is, with the usefulness of PA data for helping managers plan their agronomic decisions.

In the economics of PA, one must distinguish between managed inputs (which are factors that affect crop yield and are controlled by the farmer, such as seed type and amount, fertilizer administration, irrigation, and labor), from non-managed factors (such as rainfall, temperature, and various soil characteristics), given that the crop yield responses are a function of both types of elements and their interrelatedness. However, only decisions about managed inputs are relevant for economic evaluation, as non-managed factors, which are mostly random, make this task much more difficult to accomplish. This aspect makes econometric models especially attractive, given that they entail observed variables, unobserved factors, and randomness. In a different approach, that is less statistical but more economical, see [4] for an economic model of corn management. On the other hand, ref. [5] performed a study to determine the economic benefits of PA in six farms in Australia, applying standard economic tools such as gross margin calculations and discounted cash flow analysis, contributing to the debate about the profitability of PA. Here, economic aspects such as those addressed by the previously referenced authors are not addressed, given that the data available was exclusively from PA not including the observation of economic variables.

The above-mentioned authors concluded that the use of, and benefits from, PA technology are farm specific, varying with farmer preferences and characteristics. Therefore, this work is more concerned with presenting a general methodology of management evaluation based on spatial econometrics and that can be applied to a variety of situations and case studies, than with the particular relevance of the results obtained.

This paper uses PA data from a large Portuguese farm producing maize. Data were collected following the principle of dividing the field into smaller management zones that are more homogeneous for the properties of interest, rather than the field as a whole; and monitoring a large variety of crop features, such as fertilizer use, weather conditions, soil nutrients and characteristics, irrigation, and crop yields, among others. An important challenge that was faced during this study concerned the management of such a huge data set, together with performing a meaningful explorative data analysis, in order to reduce the raw information into useful variables for model specification and estimation. Ref. [6] called attention to the problems raised by the consequent accumulation of huge amounts of data by PA, creating the need for useful tools specifically designed for data storage, processing, management, and analysis.

While most economic and econometric studies have focused on the explanation of yield levels, the main purpose of this study was to evaluate management practices, and it focused on impact that management practices and decisions have on yield changes. It is feasible to assume that after a crop campaign, farmers adapt and adopt more strategical and tactical options for the next crop campaign. These decisions might have positive, negative, or neutral impacts on yield, not always providing the desired outcome for the farmer.

Thus, the relevance of the study regards the identification of management factors determining maize yield, their critical values and the quantification that strategic options regarding agronomic inputs have in the particular case of maize crops yield, in the specific context of the farm analyzed.

As a main contribution, this work illustrates how spatial analysis tools and spatial econometric models can be used to model crop yield, in order to evaluate farmer decisions on managed crop inputs. Our model specification takes into account unobserved spatial heterogeneity (due to omitted variables specific to the spatial units), nonlinearities in the response of crop yield to production factors, managed inputs, and un-managed factors. It is sufficiently general to be applied to a variety of farms and types of crops. Thus, in general, the approach is intended to be a framework for assessing potential optimal levels of managed inputs in each farming context.

The remainder of the article is organized as follows: Section 2 presents the background, focusing on the determinants of corn crops and previous work on econometric modelling of corn yields. Section 3 is devoted to the data, methods used in the empirical study and results obtained. Finally, Section 4 concludes.

2. Background

2.1. Maize Production in Portugal and the World

Maize is one of the most produced cereals in the world. This cereal currently presents numerous applications, whether for silage, animal feed, or the food industry, such as flour and starches, or even to produce renewable energy (bioethanol and biogas) or biodegradable materials (fibers and bioplastics). Nowadays, according to [7], maize is grown in more than 160 countries, from the most advanced to the self-subsistent, being one of the most productive crops, with an annual world production in 2019 of 1148 million tons per hectare.

In the Portuguese agricultural context, the cultivation of maize appears intimately linked to irrigation, which is especially crucial in Mediterranean environments. Presenting itself as the most important arable crop in Portugal, in 2019 it occupied around 83,360 hectares of cultivated area, with an annual production of 748,780 tons per hectare, in the same year [7]. During the period 1961 till 2018 Portugal and the rest of the world verified globally an increasing trend of the average maize yield registering, in 2018, an average maize yield of 8.56 and 5.92 tons/ha per year, respectively. From the mid-nineties the average yield in Portugal surpassed the global yield, denoting that Maize production in Portugal became more efficient [7].

2.2. Determinants of Maize Crop

Maize shows a great adaptability, and its successful cultivation mostly depends on the right choice of variety, so that the length of the growing stage of the crop matches the length of the growing season and the purpose for which the crop will be grown. The optimal choice of sowing date is the cheapest tool for improving the grain yield. Each variety has an optimal sowing date and the greater the deviation from this optimal date (early or late sowing), the greater the yield losses [8].

Regarding the types of soil and, especially in Mediterranean environments, under irrigation conditions, a good circulation of water and air, a high usable capacity for water, the availability of nutrients in the soil, and ideal weather conditions, give this crop a better response. See [9] for a study on the effects of different soil properties and irrigation treatments in northwestern China on maize crop yield.

Temperature and other climatic factors impact on maize yield. An extremely important climatic factor, identified in several agronomic studies, for predicting maize yield is solar radiation, where a large part of maize's dry matter comes from the fixation of CO_2 by the photosynthetic process; being considered a highly efficient plant in its use of light. Therefore, long periods of cloudiness, associated with frequent rainfall, and, thus, suppressing active photosynthesis, are associated with a decrease in maize yield. On the other hand, [10] analyzing the effects of extreme heat in maize production in the US shows that the crop increases gradually with temperatures, but when they are above 30 °C, or in extreme days and seasons with relatively weak rainfall, the production of maize is clearly negatively affected. These results were also confirmed by [11], who analyzed the effects of weather on yields of several crops including corn, in the US between 1950 and 2005. Moreover, ref. [12], investigating the effects of weather conditions on wheat and corn yields for several provinces in Italy from 1900 till 2014, using quantile autoregressions, concluded that high temperatures and dry weather conditions have negative impacts on yields, with being corn yield more negatively affected by adverse weather.

Being a spring–summer crop, sown in the months of March to May, and under the climatic conditions in Portugal, it is extremely important to pay attention to the crop's water requirements. The stages of plant development that are most critical to water deficiency correspond to the beginning of flowering, the fertilization period, and, finally, the grain filling phase.

Finally, fertilization is crucial to obtain the potential yield of the maize crop. The nutrients most absorbed (macronutrients) by this plant, which are fundamental to its growth, are Nitrogen (N), Potassium (K), and Phosphorus (P). Starting with Nitrogen, its management is difficult. Since it is a very soluble compound, it is easily lost by being washed along the soil profile. Especially in irrigated conditions, this can happen if the amount of water used for irrigation is very high, causing surface runoff, dragging the nitrogen, and, consequently, its leaching. Owing to this, it is very difficult, or practically impossible, to forecast a precise amount of nitrogen fertilization. To compensate for nitrogen excess, phosphorus has the function of stimulating root growth, increasing the mechanical resistance of the stems, and positively influencing flowering. This macronutrient is poorly soluble and can easily become unavailable to plants. In addition, if the soil has an acid pH, phosphorus tends to bind to the iron and aluminum present in the soil; thus, becoming unavailable for plant uptake. If the soil is alkaline, phosphorus binds to calcium forming a poorly soluble compound, becoming difficult for plants to absorb. Lastly, potassium is the macronutrient most absorbed after nitrogen, contributing to the improvement of the quality of the maize. In other words, it is less washed out than nitrogen but more than phosphorus. In addition, if bound to clays, it becomes unavailable and impossible for plants to absorb. On the other hand, it is important to note that excessive applications of nutrients result in inefficiencies in nutrient use and imbalances, with damage to future productivity and the environment ([13]). See [14] for a review study on historical and geographical perspectives on the association of maize yield and nutrient uptake.

2.3. Time and Space in Agricultural Econometrics

Despite the extensive literature about planted acreage by agricultural economists, there are gaps in the literature that remain to be addressed. Most of the studies conducted disregarded the spatial dependence and heterogeneity present in the data; thus, ignoring the spatial and time variability of crops, which an econometric analysis could explain. Only a small number of studies applied spatio-temporal regression and techniques to analyze and understand the complex phenomena studied in PA. Examples are [15,16], which used spatial error models and a group-wise heteroskedasticity model to estimate the optimal site-specific fertilizer (nitrogen) needed in a corn crop; ref. [17], who tested whether corn yield response to nitrogen and phosphorus is spatially and temporally stable, as well as evaluating the profitability of a variable rate of fertility management strategy over a five year period, using geostatistical regression models accommodating significant spatial autocorrelation among the observations; ref. [18], who used a three-year panel of on-farm corn yield experiments and classic spatial regression models, to investigate the profitability and stability of site-specific nitrogen fertilizer; and finally [19], who focused only on the spatial dimension, to analyze the spatial heterogeneity of crop yield responses to agronomic treatments, using mixed geographically weighted regression (GWR) models.

It was in the early 1990s, that farmers started to use yield monitors to produce yield maps for their fields ([20]). However, the interpretation of these maps can be complicated, since crop yield is associated with both transient and permanent crop factors. Transient factors, include insects, diseases, planter or applicator malfunctions, and measurement errors that result from the transport, mixing, and cycling of the grain ([21]). These are site-specific factors that vary from year to year. Permanent spatial effects, such as landscape position, terrain attributes, erosion, and soil properties, can also alter, alongside the transient factors, the spatial patterns in yield maps [22,23]. According to [24], data from multiple years are needed to identify recurring spatial yield patterns and, therefore, understand the effect of this factor in the crop yield.

As for the terrain attributes, topography is one of the most obvious causes for yield variation; being mostly unchangeable, it can be used to explain variation. For example, maize silage yields are highest at lower positions, rather than at mid-slope or summit positions (see [25,26]). Usually, the combination of the effect of terrain attributes, such as elevation, slope, and curvature, with the plant available water, highly influence the crop yield. In years with below-normal rainfall, areas with greater slopes and convex curvatures normally have less available water and lower yields than areas lower on the hillslope and with concave curvatures ([27]).

Since some of the above-mentioned characteristics of soil and terrain are not always observed, they contribute to the presence of omitted spatial heterogeneity in modelling, which can be controlled by including spatial terms in the regressions. This was the strategy followed in this paper.

In the field of weather data, there is still no agreement regarding the appropriate spatial or temporal aggregation of the data. In the study included in [28], these variables were measured differently. Typically, monthly measurements are used in most maize yield response models, as in [29,30]. However, a monthly data proxy does not provide a good specification for the climatic effects, because of the year-to-year variability of the crop. Each month varies by location and year, since the planting dates and weather events also vary, putting the maize at different development stages at different months each year. Hence, the mentioned author suggested measuring them by growth stage of the crop, allowing for a better specified model, where all the different crop planting dates can be taken into account.

Typically, studies have only included precipitation and temperature as weather variables in regression analysis, mainly due to the lack of estimates available for other climatic data, as is the case with solar radiation. According to [31], there is a positive relationship between the final maize yield and the cumulative solar radiation available which can be observed, especially in the third and fourth stage of maize's life cycle, since the plant's leaves are fully developed, more efficiently intercepting solar radiation for photosynthesis.

For the reasons mentioned in the above paragraphs, weather variables were transformed as daily averages and calculated at different stages of crop growth, to be used independently as variables in regression.

To conclude, the emergence of PA has brought a more precise and thorough analysis of spatial variations, with the use of complex technologies, such as the global positioning systems (GPS) and geographical information systems (GIS) [32]. This fact, together with the complexity of the interactions between variables influencing maize yield and quality in time and space, brings about the need of a multivariate approach to the analysis of the crop yield determinants. This is the approach followed in this work, which will be presented in the following sections.

3. Data, Methods and Results

3.1. Data

The data used in this study were collected and provided by Portuguese firms using precision agriculture in maize cultivation. The maize exploitation in question is considered large, with approximately 542.5 hectares, in the years 2017 and 2018.

The companies have been developing efforts to collect as much data as possible in recent years. The entire maize farms were divided into 54,265 geo-referenced spatial units (ids). This unit definition originated from considering a 10-by-10-m square grid, which resulted in 100-square-meter spatial units. Although being part of more irregular parcels and sub-parcels, these smaller spatial units became the reference units for farm management and monitoring.

In order to assess management practices and options and their impact on maize yield, the analysis was carried out at the spatial unit level (id).

Concerning the data collection method, at the end of the season, the harvesters enter the farm and collect the maize. From these machines, with a width of 6 m, a shapefile is created, with the kilograms of the harvested maize in those spatial units. This data are then processed and filtered, and the errors due to the fragility of the machines are corrected.

For this study, the variable of interest is the average annual maize yield (y) measured in tons per hectare by id. This is determined by the dry weight of the harvested maize in a parcel/sub-parcel, indexed by the number of hectares of maize planted over time.

In Figures A1 and A2 from Appendix A, we can see the spatial distribution of both yield (y) for 2018 and the variation in yield (Δy) for the same year. From Figure A1, it is possible to observe a great variability of yield in space. Combining the analyses of Figures A1 and A2, a variety of situations combining the size of the level of maize yield with the size of its variation are also noticeable; that is, high level areas may show low increases of yield, medium or high, and low yield areas may be related to high increases from the previous year, medium or low.

The spatial dependence for both y and Δy can be assessed in Figures A3 and A4 in the Appendix A. These figures plot, respectively, each variable against its spatial lagged value (obtained using a rook contiguity matrix). In particular, in Figure A3, it is possible to identify some spatial units that had zero or nearly zero production in 2018, despite being planted (facing a heavy decrease in production in comparison with the previous year's campaign).

Apart from monitoring maize yield, climate data such as temperature in °C, precipitation in mm, relative humidity in percentage points, global solar radiation in W/m^2, and wind speed in km/h were collected daily for each sub-parcel with a 10-min frequency.

For the weather-related variables, the approach used in [28] was followed; being, consequently, those variables measured by maize development stage rather than by month, as is commonly seen in most agricultural econometric studies. The reason for this is the year-to-year variability of the crop and all factors associated with it. In this manner, in order to create variables by growth stages rather than by month, information was gathered on important dates in the maize life cycle, where four stages of maize growth were defined according to Table 1, following [28].

Table 1. Definition of the maize growth stages.

Stage	Plant Activity	Starting Date	Ending Date
1	Emergence of the seedling from below the soil	Planting date (March/April/May)	Emergence date (April/May/June)
2	Early vegetative growth	Emergence date (April/May/June)	Flowering start date (June/July)
3	Flowering	Flowering start date (June/July)	Flowering end date (June/July/August)
4	Grain fill until maturity (harvest)	Flowering end date (June/July/August)	Harvest date (September)

Note: Both stages 1 and 3 only last about 15 and 10 days, respectively. Source: Own elaboration.

To obtain the weather data used in the model estimation, the following procedure was implemented. First, for each variable, the daily mean values were calculated. Then, with these daily values, the average of daily mean values (on the five climatic observed variables) was computed for each year (2017 and 2018) and each growth stage in Table 1. This high-frequency climate data provide, on one hand, a huge and rich dataset to measure climate effects on each stage, but, on the other hand, several variables that are highly correlated, inducing multicollinearity problems if all are included in linear regressions (naturally, temperature is correlated with all other climatic variables, such as relative humidity or global solar radiation among others). In this regard, more than one hundred climatic variables were preliminary analyzed and tested. The majority were dropped due to being insignificant for explaining the dependent variable.

Two other important sets of variables were collected: macronutrients and chemical treatments (herbicides and insecticides applied on different dates/stages for each sub-parcel).

To control for vegetation status, vegetative stress, and general crop health the normalized difference vegetation index (NDVI) of each spatial unit was assessed. NDVI is a satellite-derived vegetation index based in the soil vegetation cover, being the most widely used proxy for vegetation productivity. There is a strong relationship between the NDVI and crop yields. This index ranges between −1 and +1, where negative NDVI values represent non-vegetation surfaces, such as water bodies/masses, values close to zero refer to bare soils, and high values indicate strong vegetative cover. That is, the NDVI is a numerical indicator that analyzes the amount of live green vegetation in satellite images. The greener the observed vegetation is, the higher this index becomes. The information retrieved by the NDVI helps to better understand the behavior of crops during life cycle events and their response to natural or anthropogenic disturbances in agricultural ecosystems. See [33] for a commentary review on the use of NDVI.

In this study, during the crop campaign, 41 and 56 measures of NDVI in 2017 and 2018, respectively, were made for each sub-parcel. The first observed NDVI at an early stage was chosen to depict the potential maize seed vigor, given that in this early stage it is less prone to the interferences of other factors that affect yield productivity.

The effort and investments in data collection enabled defining several variables that were observed in 93% of the spatial units (50,547 spatial units) for the years of 2017 and 2018, in order to have a balanced panel.

For these variables, the same transformations and procedures performed on the climate variables were computed. In preliminary data analysis, most were not shown to be significant in explaining the behavior of maize production, and, as a result, were dropped from the estimation. Table 2 provides a summary of the final variables used in the empirical analysis of this article, after the preliminary selection procedure.

Table 2. Key variables for analysis.

Variable	Description
y	Maize yield (tons/ha)
Δy	Annual change in Maize yield in 2018 (tons/ha)
N	Total Nitrogen (Kg/ha)
P	Total Phosphorus (Kg/ha)
K	Total Potassium (Kg/ha)
I	Total Irrigation (mm/ha)
T_S_i	Average daily Temperature on Stage i (i = 1 to 4)
Seeds	Dummy variable equal to 1 if there was a change of Seeds used in previous year on the spatial unit, and 0 otherwise
Treat	Dummy variable equal to 1 if there was a change in Treatment (herbicides, insecticides) from the previous year on the spatial unit, and 0 otherwise
Soil	Dummy variable equal to 1 if the soil is clayey and equal to 0 otherwise
ndvi	First observed NDVI (early stage).

While Table 2 shows the key available variables, Table 3 shows descriptive statistics for the above variables, which were used in the empirical model.

Table 3. Descriptive statistics for 2018.

Variables	N	Minimum	Maximum	Mean	Std. Deviation
y	50,547	0	24.82	16.50	3.87
Δy	50,547	−21.80	24.41	3.88	9.34
N	50,547	0	407.54	358.26	62.71
P	50,547	0	171.10	147.30	38.92
K	50,547	0	180.88	87.15	58.64
I	50,547	507.29	645.78	564.67	40.82
T_S1	50,547	13.40	18.79	16.77	1.12
T_S2	50,547	17.99	19.99	19.32	0.41
T_S3	50,547	20.12	24.70	20.55	0.64
T_S4	50,547	21.05	22.27	21.76	0.35
ndvi	50,547	0.14	0.36	0.20	0.05
Soil	50,547	0	1	0.50	0.50
Treat	50,547	0	1	0.30	0.46
Seeds	50,547	0	1	0.50	0.50

In a brief summary, Table 3 reveals that the average yield in 2018 was 16.5 tons/ha, and on average, there was an increase of 3.88 from the previous year, although with a great dispersion. Additionally, one can see that, while some spatial units had a production of zero, they all had some sort of nutrients applied and irrigation (the minimum values of *N*, *P,* and *I* were considerably above zero). Nitrogen was the nutrient used with the largest intensity, with an average around 360 Kg/ha, while the consumption of phosphorus and potassium was, on average, much lower, being, respectively, 147 and 87 Kg/ha. On the other hand, the use of potassium was the factor that varied the most within the farm spatial units.

As expected, the higher the maize growth stage, the higher the average temperature. The temperature variability was remarkedly higher in the first stage. The maximum average temperatures registered were below 25 degrees, not threatening crop productivity by heat stress.

Finally, the dummy variables are also worth noting, showing that 50% of the spatial units had a clayey soil (against 50% sandy soil), the treatment of herbicides/insecticides changed in 30% of the spatial units, and the type of seeds changed in 50% of the spatial units.

3.2. Methods and Results

As most geo-referenced variables are spatially autocorrelated and/or present spatial heterogeneity, spatial regression models are more appropriate than models that do not take spatial autocorrelation into account, as is the case of the linear model estimated by OLS. However, the OLS model is first fitted to obtain regression diagnostics for the spatial dependence of the residuals, with four statistical tests then being conducted to detect the presence of this spatial effect in linear models, such as the Moran test ([34]), the simple lagrange multiplier (LM Lag and LM Error) and their robust version (robust LM lag and robust LM error), as in [35,36]. The results can be seen in Table 4, showing clear evidence of spatial dependence.

Table 4. Statistical tests.

	Statistical Value	***p*-Value**
Lagrange Multiplier (lag)	111,070.210	0.0000
Robust LM (lag)	108.396	0.0000
Lagrange Multiplier (error)	123,629.758	0.0000
Robust LM (error)	12,667.944	0.0000

To control for spatial dependence, we followed Kelejian and Prucha’s approach [37], in which they advocated models that include both endogenous spatial interaction effects (by a spatial lagged dependent variable term) and spatial interaction effects among the error terms, leading to the so-called SARAR(1,1) model (spatial autoregressive of order 1 in the dependent variable and autoregressive of or-der 1 in the error term).

Although the data generated by the PA are sufficiently rich to allow the identification of many variables, it is natural, however, that some of the causes that influence the crop yield are not observed or even measurable, leading to the presence in the modelling process of unobserved heterogeneity. If the latter is correlated with the other variables in the model, then the usual estimation methods are inconsistent. However, with panel data it is possible to eliminate unobserved factors that are constant in time, i.e., factors specific to the spatial unit, using data transformations such as fixed effects or first differences. For example, in the data set used in this article, there are very few variables available that characterize the terrain attributes, and none regarding the topography of the spatial units. Given that we have a spatial panel data from 2 years (2017 and 2018), we can apply the mentioned transformations to remove these unobserved factors that are constant over time and, thus, eliminate the possible source of endogeneity that induces inconsistency in estimation. It is well known for panel linear models with only two periods of time that both transformations (fixed effects and first differences) should lead to the same results. Here, for sake of simplicity and convenience in estimation, first-differences transformation was chosen.

For the purpose of evaluating management practices, the main interest is to assess how farmer-controlled variables impact the variation in maize yield, such as choices about nutrient use, irrigation, and change in treatments and the type of seeds employed. Therefore, in the specification of the SARAR(1,1) model, those variables were included as explanatory variables. Climatic variables were included, as well as control variables. The squares of continuous variables were also considered to account for nonlinearities in model specification, given the complexity of the relation between agronomic inputs and crop yield and the absence of theoretical models to guide the empirical model specification.

Finally, the estimated model is

$$\mathbf{y}_t = \rho\mathbf{W}\mathbf{y}_t + \mathbf{x}_t\boldsymbol{\beta}_1 + \mathbf{x}_t^2\boldsymbol{\beta}_2 + \theta\mathbf{ndvi}_t + \sum_{j=1}^{4}\gamma_j\mathbf{T\_Sj}_t + \delta_1\mathbf{Seeds}_t + \delta_2\mathbf{Treat}_t + \delta_3\mathbf{SeedsTreat}_t + \delta_4\mathbf{Soil} + \boldsymbol{\varphi} + \boldsymbol{\varepsilon}_t \quad with \quad \boldsymbol{\varepsilon}_t = \lambda\mathbf{W}\boldsymbol{\varepsilon}_t + \mathbf{u}_t, \quad t = 2017,\ 2018 \tag{1}$$

where $\mathbf{W}$ is the (N $\times$ N) spatial weigh matrix taken as known and non-stochastic; $\mathbf{y}_t$ is a (N $\times$ 1) with the observations of maize yield in year t; $\mathbf{x}_t$ is a (N $\times$ 4) matrix with the observations of the nutrients and irrigation in year t; $\boldsymbol{\beta}_j,\ j = 1,2$ are (4 $\times$ 1) vectors of unknown coefficients; $\mathbf{ndvi}_t$ is a (N $\times$ 1) vector with observations of the index NDVI in year t; $\mathbf{T\_Sj}_t$ j = 1, . . . , 4 are (N $\times$ 1) vectors with observations of temperature variables in year t; $\mathbf{Seeds}_t$, $\mathbf{Treat}_t$, and $\mathbf{SeedsTreat}_t$ are (N $\times$ 1) vectors with observations in year t of the dummies *Seeds, Treat,* and their interaction, respectively; **Soil** is a (N $\times$ 1) vector with observations of the dummy *soil* (does not change over time); $\theta,\ \gamma_j,\ j = 1,\ldots,4,\ \delta_j,\ j = 1,\ldots,4,$ are unknown coefficients; $\boldsymbol{\varphi}$ is a (N $\times$ 1) vector of unobserved factors specific to the spatial unit (constant in time), possibly correlated with the other observable variables in the model; $\boldsymbol{\varepsilon}_t$ is the error term of the model in year t; $\mathbf{u}_t$ is an idiosyncratic error, both (N $\times$ 1) vectors; and ρ and λ are the unknown spatial parameters. Note that to avoid unstable behavior, the constraints on the spatial parameters require that $|\rho| < 1$ and $|\lambda| < 1$. Here the spatial matrix $\mathbf{W}$ was calculated based on the contiguity queen criterion.

Applying the first differences transformation in Equation (1), all variables and factors that are constant in time are eliminated, leading to,

$$\Delta\mathbf{y}_t = \rho\mathbf{W}\Delta\mathbf{y}_t + \Delta\mathbf{x}_t\boldsymbol{\beta}_1 + \Delta\mathbf{x}_t^2\boldsymbol{\beta}_2 + \theta\Delta\mathbf{ndvi}_t + \sum_{j=1}^{4}\gamma_j\Delta\mathbf{T\_Sj}_t + \delta_1\Delta\mathbf{Seeds}_t + \delta_2\Delta\mathbf{Treat}_t + \delta_3\Delta\mathbf{SeedsTreat}_t + \Delta\boldsymbol{\varepsilon}_t \quad t = 2018 \tag{2}$$

where the operator Δ gives the change in year 2018 from 2017 for each variable. The model in Equation (2) will be the one used for estimation purposes. However, for sake of interpretation of the coefficient estimates, it is more appropriate to use the untransformed model in Equation (1).

Besides considering the errors of Equation (2) as autocorrelated, the presence of heteroskedasticity is also acknowledge, following [37,38]. Estimation was performed with the GMM estimator of [38], since the first differenced data refers to a cross-section of one year. For the SARAR(1,1) Model in (2), a robust estimator of the covariance matrix in presence of both spatial heteroskedasticity and autocorrelation was considered, according to [38].

To interpret the effect of each of the x variables, ceteris paribus, one has to take into consideration the quadratic term. Therefore, the effect of changing x by one unit is given by $\beta_1 + 2\beta_2 x$. This means that the effect is specific to the spatial unit and is a function of the level of x it consumes.

The results of the GMM estimation of model (2) with heteroskedasticity robust standard errors can be found on Table 5. For the GMM estimation, the additional instruments were $\mathbf{Wz}$, $\mathbf{z}$ being all the independent variables.

Table 5. Spatially-weighted two-stage least squares with heteroskedasticity robust standard errors for the SARAR(1,1) model explaining the annual maize yield.

Variables	Coefficient	Std.Error	z-Statistic	Probability
constant	−3.26400	0.74712	−4.37	0.000
Wy	0.19722	0.01783	11.06	0.000
N	1.16329	0.08493	13.70	0.000
N^2	−0.00130	0.00012	−11.30	0.000
P	0.25149	0.04668	5.39	0.000
P^2	−0.00125	0.00020	−6.24	0.000
K	0.22823	0.00852	26.79	0.000
K^2	−0.00166	0.00006	−29.39	0.000
I	0.26508	0.01983	13.37	0.000
I^2	−0.00021	0.00001	−13.96	0.000
ndvi	12.80467	2.19045	5.85	0.000
T_S1	−2.44472	0.14507	−16.85	0.000
T_S2	−7.42977	0.55548	−13.38	0.000
T_S3	−2.58341	0.13634	−18.95	0.000
T_S4	−13.33222	0.59488	−22.41	0.000
Seeds	0.29953	0.22001	1.36	0.173
Treat	10.50346	0.85817	12.24	0.000
Seeds Treat	−9.51526	0.74883	−12.71	0.000
lambda	0.92361	0.00333	277.11	0.000

Pseudo R-squared = 0.9350.
n = 50,547

Table 5 shows a very high value for the pseudo-R-squared, suggesting that the model provides a very good fit of the data. It also shows the effects on the annual variation of maize yield of several agronomic management variables, namely *N* (nitrogen), *P* (phosphorus), *K* (potassium), *I* (irrigation), *Seeds* (implying a change of the seeds used in previous year), and *Treat* (indicating a change in the treatment from previous year).

Table 5 shows that all variables were statistically significant at a 5% level, except for the dummy indicating change of seeds.

There are several important conclusions that can be drawn from Table 5.

First, one can notice that *N*, *P*, *K*, and *I* all show negative signs on their squared terms, meaning that these variables relate to the variation of maize yield as an inverted u-shape functional form. Consequently, the effect of these variables is not constant, and it changes sign from the turning point of the curve, which can be seen as the value of these variables that maximizes the yield. These values are included in Table 6, together with some descriptive statistics.

Table 6. Nutrients and irrigation values maximizing the average maize yield, and respective descriptive statistics.

Variable	Maximizer (M)	Minimum	Maximum	Mean	% Above M
N	447.04	0	407.54	358.26	0.%
P	100.84	0	171.10	147.30	84.8%
K	68.76	0	180.88	87.15	27.6%
I	645.90	507.29	645.78	564.67	0%

Table 6 shows that the quantity of nitrogen (*N*) that maximizes the yield on average is higher than the maximum value observed, meaning that for all the spatial units increasing *N* will increase the average maize yield, but with diminishing returns.

The quantities of potassium (*K*) and phosphorus (*P*) that on average maximize the maize yield are below the mean observed in the sample, with a large percentage of spatial units (almost 85%) showing a use of phosphorus above the maximizer level, while this percentage drops significantly for potassium (28%), meaning that on average, for these units, increasing these nutrients will have a negative impact on average yield. This result may indicate that the farm is operating levels of P that are too high in a large percentage of spatial units.

Finally, the irrigation level that maximizes the yield in average is above the maximum irrigation registered in the sample. This means that, all the arable land is in a situation in which increasing units of I will have positive impacts on the average maize yield (at a diminishing rate).

Increasing the average temperature in each maize growth stage will, on average, decrease the crop yield, especially in the fourth stage, where one more degree of temperature will provoke an average decrease of 13 tons/ha, which is a very large impact. In the first and third stages, the impacts are smaller and similar, being around -2.5 tons/ha.

Regarding the NDVI, it presented a positive correlation with the yield variation, as expected.

Regarding the decisions about changing the seeds and changing the treatments, because of the interaction term, one may conclude that in those spatial units where treatment was not altered from the previous year, the change of the type of seed had no statistically significant effect on the maize yield, on average. The change of treatment in units where there was no change of the type of seed was successful because it led, on average, to an increase of the crop yield. The change of both the treatment and the type of seeds was also revealed to be successful, but with a much smaller impact than the latter.

4. Conclusions

This article illustrates how spatial econometric regression models can be useful to evaluate managerial agronomic decisions concerning crop production with PA data.

One important contribution of this work lies in the proposed model specification for the determinants of annual maize yield variation with the methodology used for estimation, given that the literature on this subject is scarce. This specification was a major challenge, given the enormous quantity of data typical from PA case studies, and relying on a preliminary computer-intensive data analysis. The final model was revealed to fit the data very well. It includes nonlinearities inducing heterogeneous effects on the mean of yield variation, which depend on the specific characteristics of the cultivated spatial units, being in line with the paradigm of PA. Moreover, it controls for spatial heterogeneity and spatial dependences recurring to spatial terms and spatial econometric techniques.

The results from this model suggested that decisions concerning the change in treatments (herbicides, insecticides) in the current year relative to those used in the previous year, incurred, on average, an increase of the maize crop yield, while when accompanied by a change of type of seed, this effect was attenuated.

Given that, on average, yield increased, the results show that the management practices for the current year were, in general, successful.

On one hand, the results seem to indicate that the management of nitrogen and irrigation have room for improvement, without harming, on average, the crop yield, where the levels observed in all spatial units were below the optimal level that maximized the yield.

Management of phosphorus and potassium should be balanced once a large percentage of the spatial units are still above the point where an increase of this nutrient has, on average (and ceteris paribus), a negative effect on crop yield.

The model also constitutes an important decision tool for management when the effect of each of the manageable input variables is not constant and equal for all spatial units, but depends on their level in each unit.

Finally, the model could be used to simulate the expected yield given expected values for the average temperature in each maize growth stage, and for nutrients, irrigation, and the decision about changing or not the type of seeds and treatment; with it being one more instrument that managers have at their disposal to define their agronomic decisions. More importantly, the analytical approach introduced in this work might provide a framework for managers to assess optimal levels for managed inputs for each specific farming context.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

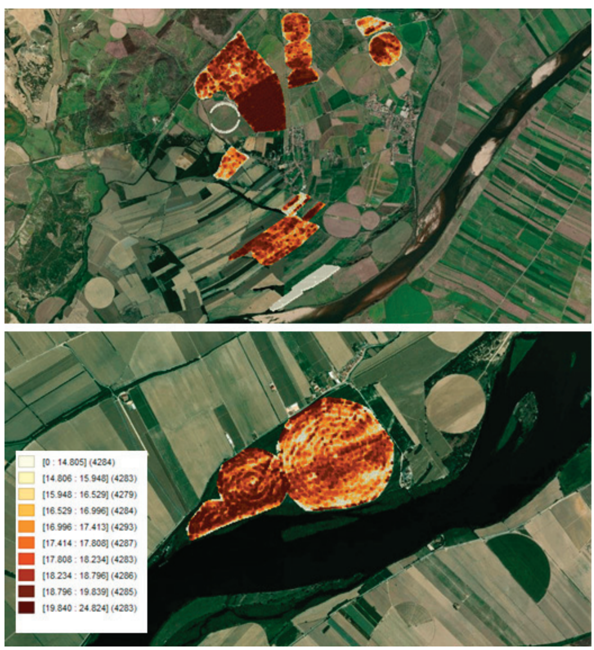

Figure A1. Maize yield (y) in 2018 per quantile.

Figure A2. Variation in maize yield (Dy) in 2018 per quantile.

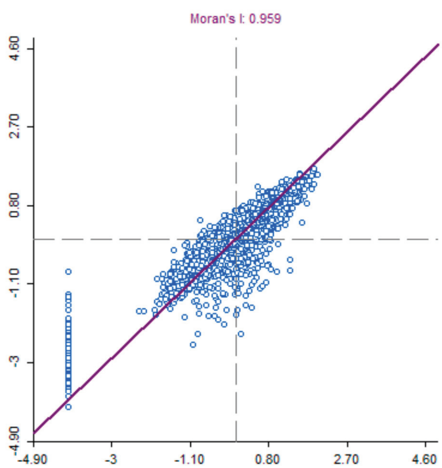

Figure A3. Moran's I for maize yield (y) in 2018. The standardized values of y are plotted against the standardized values of Wy.

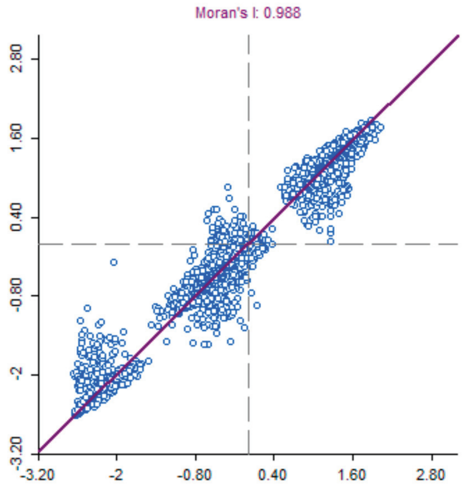

Figure A4. Moran's I for the variation of maize yield (Δy) in 2018. The standardized values of Δy are plotted against the standardized values of WΔy.

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standards

MDPI

Review

An Overview of Indoor Positioning and Mapping Technology Standards

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Abstract: Technologies and systems for indoor positioning, mapping, and navigation (IPMN) have rapidly developed over the latest decade due to advanced radio and light communications, the internet of things, intelligent and smart devices, big data, and so forth. Thus, a group of surveys for IPMN technologies, systems, standards, and solutions can be found in literature. However, currently there is no proposed solution that can satisfy all indoor application requirements; one of the biggest challenges is lack of standardization, even though several IPMN standards have been published by different standard developing organizations (SDOs). Therefore, this paper aims to re-survey indoor positioning and mapping technologies, in particular, the existing standards related to these technologies and to present guidance in the field. As part of our work, we provide an IPMN standards system architecture consisting of concepts, terms, models, indoor positioning technologies, software and tools, applications, services and policies, and indoor mapping and modelling; and, we present IPMN standards developed for our projects in practice, such as multi-source fusion positioning data interfaces; seamless cooperative positioning service interfaces; content model for indoor mapping and navigation, and specification for digital indoor map products.

Keywords: indoor positioning; mapping and modelling; indoor navigation; standards system

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1. Introduction

Positioning technologies can be classified into two categories according to the application scenario: outdoor positioning and indoor positioning. The increasing demand for location-based services (LBS) is gradually extending from outdoor to indoor, and indoor positioning systems (IPS) or indoor localization systems (ILS) are attracting scientific and enterprise interest because there is a huge market opportunity for applying indoor positioning, mapping, and navigation technologies [1]. According to Technavio, the indoor positioning and indoor navigation (IPIN) market has the potential to grow by USD 23.03 billion during 2021–2025, and the market's growth momentum will accelerate at a CAGR of 33.21% [2]. Due to the benefits of indoor positioning, mapping, and navigation (IPMN) technologies and systems, numerous indoor applications have been deployed in large buildings—such as hospitals, airports, shopping malls, and train stations—to guide visitors to their destinations [3]. However, IPS applications still face several technical and non-technical challenges, such as location privacy, the quality of positioning services, and the availability of indoor maps [4].

Different techniques, technologies, mechanisms, methodologies, systems, platforms, applications, and standards related to indoor positioning have been proposed to provide indoor localization services to improve the services provided to the users [5]. Mendoza-Silva et al. [6] provide readers with a meta-review of indoor positioning systems, aiming to guide the reader to easily find further details on each technology used in IPS. Nevertheless, the problem of positioning in indoor environments is far from being solved, and there is still no satisfactory IPS capable of being used in all indoor scenarios with standard behavior [7].

Indoor modelling and mapping play a key role in indoor positioning and navigation systems. The scientific and technological progress in 3D spatial data acquisition as well as 3D city and building modeling have been evolving into more sophisticated hardware, software, standards, techniques, and uses specific to indoor modeling and mapping [8]. With regard to indoor environments, geographical information system (GIS) technologies and tools can also undoubtedly be integrated to enhance an IPS functionalities; for example, the utilization of GIS includes indoor data acquisition and management, geospatial analysis, route planning optimization, and so forth [9]. Moreover, cartography has evolved and improved the way maps are depicted and communicated, meanwhile the increasing deployment of indoor positioning systems provides forceful motivation for improving the cartography of indoor maps [10].

Standardization plays a significant role in the process of industrialization of indoor positioning, mapping and navigation production and utilization, and it is an inevitable choice. According to the definition from International Organization for Standardization (ISO), standardization is an activity formulating common and reusable rules for practical or potential problems to get the best order in a certain range. The challenge we are now confronted with is how to popularize indoor positioning systems to realize industrialization after the basic indoor positioning technologies have matured. Standardization work is an effective means to promote this industrialization process, in the following two ways: firstly, standardization is the premise and foundation of information sharing and interoperability among various systems. In different industrial applications, most companies will adopt the specialized standards common in that industry, resulting in a waste of resources that impedes sharing and interoperability. Secondly, standardization benefits cost saving and the enhancing quality of software products. When developing indoor positioning products, standardization helps to shorten the development cycle and to improve the quality of software products. Through standardization, we can set the specifications and narrow the technologies and techniques; however, currently, there are a few standards that can serve as a guide for designing localization and proximity techniques [5]. For this reason, several standard developing organizations (SDOs) have published a series of standards for indoor positioning, navigation, and mapping, including the International Organization for Standardization and the International Electrotechnical Commission (ISO/IEC) Information technology—Real Time Locating Systems (RTLS), ISO Technical Committee (TC) 204 Intelligent Transport System (ITS), IEEE standard for robot Map Data Representation (MDR), ISO TC211 Geographic Information standards, Open Geospatial Consortium (OGC) standards for spatial data encoding and exchanging, Industrial Foundation Classes (IFC) of buildingSmart, and so forth. However, since these standards are published by different SDOs for different purposes, their conformity and coordination need to be tested for specific application scenarios. For example, CityGML and IndoorGML—developed by the Open Geospatial Consortium (OGC)—provide similar frameworks for standard data models of indoor spaces, but their goals and approaches are different so how they can be used in a complementary way for applications must be clarified [11].

A review of the literature suggests that most survey articles on algorithms, modeling, techniques, technologies, systems, standards, applications, and services in the field of indoor positioning, mapping, and navigation focus on the individual arts of different technologies. Subsequently, there is a lack of an overview on indoor positioning, mapping, and navigation standards for IPS developers and applications. According to ISO 17438-1:2016, a typical intelligent transport system's (ITS) indoor navigation application usually covers indoor positioning, and an indoor map and navigation service; thus, we aim to present an overview on existing indoor positioning, mapping, and navigation technologies and standards from the viewpoint of IPS developers and service providers. The purpose is to provide a guideline for IPS developers to find suitable resource links for their applications, that is, what kind of IPS technologies and standards should be selected or integrated into applications. Furthermore, we present the requirements of the IPMN standards series, that is, from the viewpoint of a standards system, as we need to develop more IPMN standards beyond the published international standards. Consequently, we comment on some developed standards or standards in development in our project, including content model and data acquisition for indoor mapping, multi-source fusion positioning data interfaces, seamless cooperative positioning services, and so on.

The remainder of the paper is structured as follows: in Section 2, we survey the existing indoor positioning, mapping technologies and standards based on reviews in the literature. This overview provides a clue for IPS developers to search for suitable technologies and standards for specific applications. In Section 3, we discuss the requirements of an IPMN standards system, which extends the published IPMN standards. For general purposes, the standards series must cover concepts, terms, models, requirements, use cases, tools, products, and other specifications. Later, in Section 4, we focus on some standards developed for our project, which are expected to be a part of the standards system. Finally, Section 5 presents the conclusions of this paper. Moving forward, we will now discuss related work in detail.

2. Related Work

The problem of indoor navigation can be basically decomposed into three sub-problems: positioning, environment mapping, and trajectory planning [12]. Additionally, according to ISO 17438-1:2016, a typical intelligent transport systems (ITS) indoor navigation application usually covers indoor positioning and indoor map and navigation services [13]. Navigation refers to one kind of application among others, such as tracking, asset management, and so on. We consider indoor positioning and mapping as the most fundamental technologies, whose requirements of various application situations vary from each other. In this circumstance, in this section, we only briefly introduce the existing indoor positioning and mapping technologies based on a broad review of the literature and then focus on the relevant standards.

2.1. Indoor Positioning Technologies

Since there are numerous indoor positioning techniques and technologies, it is hard to present a complete survey covering all existing and emerging technologies. Numerous surveys on indoor positioning principals, approaches, methods, systems, solutions, platforms, classifications, evaluations, comparisons, challenges, and future potential directions can found in the literature [5,6,14–23].

Sakpere et al. [14] present an attractive survey of indoor positioning and navigation systems observed from literature, and they propose an overview of positioning algorithms, techniques, and technologies as shown in Figure 1. The technologies discussed include infrared (IR), ultrasound/ultrasonic, audible sound, magnetic, optical and vision, radio frequency (RF), visible light, pedestrian dead reckoning (PDR)/inertial navigation system (INS) and hybrid. The RF technologies discussed include Bluetooth, ultra-wideband (UWB), wireless sensor network (WSN), wireless local area network (WLAN), radio-frequency identification (RFID), and near field communication (NFC). The authors analyzed the pros and cons of the positioning technologies according to metrics such as accuracy, complexity, cost, privacy, scalability, and usability. However, the survey needs to be updated to cover the most recent and relevant technologies since IPSs are a rapidly evolving area. For example, the arrival of 5G, IoT, and AI as well as big data have taken indoor positioning to a new level. Therefore, we reference their classification of indoor positioning technologies as an overview of existing technologies and a guidance for indoor positioning related applications.

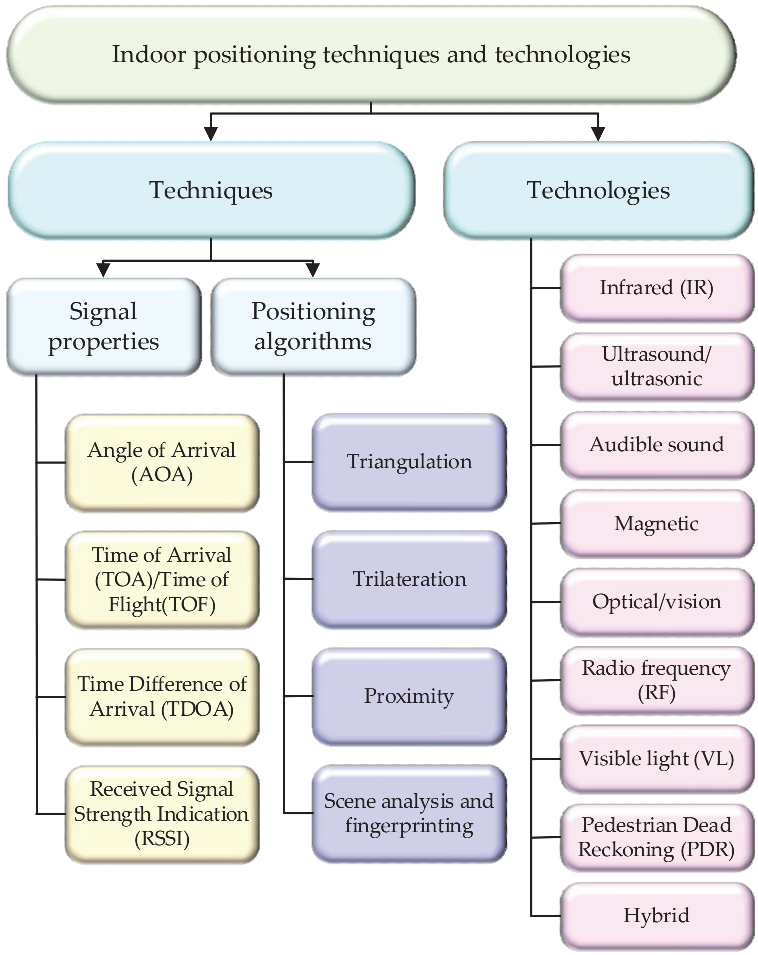


Figure 1. Classification of indoor positioning techniques and technologies [14].

Indoor positioning technologies can be classified in different ways. According to [12], localization systems are roughly divided into active and passive systems, where active systems require tracked persons to participate actively, i.e., a person needs to carry an electronic device which sends information to a positioning system helping it to infer that person's position. In contrast, passive systems use passive localization, that is, the position is estimated based on the variance of a measured signal or video process, which means the tracked person is not carrying any electronic devices to infer the user's position. Based on previous surveys on indoor positioning systems, Brena et al. [15] provide a comparison of nearly 28 technologies, which are categorized into optical (infrared, visible light communication), sound-based (ultrasound, audible sound), radio frequency (Wi-Fi, Bluetooth, ZigBee, RFID, UWB), passive/without embedded information (magnetic field, inertial, passive sound-based, passive visible light, computer vision), and hybrid technologies. The paper aims to present the evolution and trends of indoor positioning fields. Most of the technologies are partly discussed in [14] from a different viewpoint. Yassin et al. [16] present a classification of localization methods based on positioning algorithms and measurement techniques. Kunhoth et al. [17] propose a hierarchical classification of indoor navigation systems; and, the first level is grouped into computer vision-based, communication-based, and PDR-based navigation systems, where communication-based wayfinding systems are sub-grouped into RFID, Wi-Fi, visible light communication (VLC), UWB, and Bluetooth technologies. Most surveys present limitations and strengths analyses, performance evaluations, comparisons of various heterogenous technologies and systems, as well as challenges, opportunities and future research directions in this field.

From the indoor positioning device perspective, Xiao et al. [24] categorize wireless indoor localization schemes into device-based and device-free, where device-based localization refers to a wireless device (e.g., a smartphone) attached to the target that computes its location through cooperation with other deployed wireless devices; in contrast, device-free localization means the target carries no wireless devices, while the wireless infrastructure deployed in the environment determines the target's location by analyzing its impact on wireless signals. The authors also present a performance comparison of smartphone-based, tag-based, and device-free systems. Based on whether an IPS requires the deployment of dedicated infrastructure or not, the existing indoor localization systems can also be classified into infrastructure-based and infrastructure-free systems [22,23].

Zafari et al. [5] provide a detailed survey of indoor localization techniques such as AOA, TOF, return time of flight (RTOF), received signal strength (RSS), RSSI, and channel state information (CSI) based on technologies such as WiFi, RFID, UWB, Bluetooth, and systems that have been proposed in the literature. The authors grouped these technologies and systems as device-based localization (DBL), monitor-based localization (MBL), and proximity detection. In contrast to the existing surveys, they analyzed how novel systems such as Internet of Things (IoT), smart architectures (such as smart cities, smart buildings, smart grids), and machine type communication (MTC) can impact or benefit indoor localization; and, they evaluated different systems from the perspective of energy efficiency, availability, cost, reception range, latency, scalability and tracking accuracy. However, as the authors addressed, there is no system proposed so far that satisfies all these requirements. The authors highlight the use of localization in context-aware location-based marketing, health services, disaster management and recovery, security, asset management/tracking, and IoT. Finally, the authors provide a checklist of the pros and cons of different technologies and highlight their suitability and challenges for indoor localization. One of the biggest problems is that there is no standard that can serve as a guide for designing localization and proximity techniques.

Simões et al. [7] revisited the then current literature to present an expansion of the range of technologies and methodologies for assisting the visually impaired in previous works, providing readers and researchers with a more recent version of what was done and the advantages and disadvantages of each approach. The authors reorganized IPS structures into radio-based (range-based and range-free), no radio-based (inertial-based, sound-based, light-based and vision-based), and hybrid indoor positioning systems.

Many more comprehensive reviews of various positioning technologies can be found in the literature [4–6,16,17,20,21,25–30]. The main goal of most surveys is to provide a guideline for readers and IPS developers to better understand the weaknesses and strengths of each technology and system. The performance evaluation metrics usually include accuracy and precision, coverage, cost, latency, complexity, robustness, availability/usability, scalability, lower power, privacy, and security.

Currently, the fifth generation (5G) mobile network, big data, and artificial intelligence (AI) are new technologies to improve indoor 3D localization by using new radio (5G NR) technologies, Internet of Things (IoT), and machine learning probabilistic algorithms, among other technologies [31]. In 2019, 5G cellular networks started to be deployed worldwide, and the new technologies have enabled approaches for improving the performance of wireless indoor positioning [32]. For example, El Boudani et al. [33] proposed (a deep, learning-based cooperative architecture using 5G IoT networks for 3D indoor positioning, and Horsmanheimo et al. [34] present an indoor positioning platform to support the development of foreseen location-based 5G network functionalities and services. However, indoor positioning in 5G IoT networks is still a very new research area, and a recent 5G

PPP technical report [35] set out the detailed indoor 3D positioning requirements and challenges.

Although recent technologies have shown significant advances in terms of accuracy and speed, they have been used in new algorithmic arrangements to improve the quality of indoor positioning systems; and, there are continuous open efforts for guiding readers, researchers, and developers to select reliable, user-friendly, and accurate solutions for indoor positioning and navigation applications that are suitable for different scenarios. Nevertheless, the problem of positioning in indoor environments is far from being solved. There is still no satisfactory solution of an IPS capable of being used in all indoor scenarios with standard behavior [7]. One of the significant challenges is a lack of standardization; in other words, there is no standard that can serve as a guide for designing localization and proximity techniques and indoor positioning systems [5], although several international standards for RTLS and ITS have been published by ISO, which will be discussed in Section 2.3.

2.2. Indoor Mapping Technologies

With the development of smart cities, digital twins, or the metaverse, there is a growing demand for more effective spatial information acquisition, processing, modeling, representation, and visualization of indoor environments. Unlike the outdoor space, the indoor space is typically bounded and constrained by architectural structures [9]. The challenges of the structural complexity of buildings and indoor location-based applications have been growing in interest in indoor mapping and surveying.

Indoor mapping and modeling varies from that of outdoor in many ways due to the complexity and constraints of the indoor space. Therefore, indoor spatial information is acquired by mobile mapping systems (MMS), which makes it possible to acquire time-saving and fully-equipped environmental data using laser scanners from moving platforms. Research and development on multi-sensor mobile mapping systems has been ongoing since the early 1990s. Indoor mapping and modeling (IMM) has greatly accelerated in recent years given the advancements in photogrammetry, computer vision and image analysis, computer graphics, robotics, and laser scanning [36].

Two common ways to examine this literature include identifying ethical issues and the problem areas and applications. Zlatanova et al. [37] examined 35 interlinked IMM problems related to indoor map data acquisitions and sensors, data structures and modelling, visualization, applications, and legal issues and standards in the form of a problem matrix detailing existing and emerging problems, their solutions, and best practices. This problem matrix framework is evaluated and updated yearly. Gunduz et al. [8] presented a research review in the fields of information acquisition by sensors, model definition, model integration, indoor positioning and LBS, routing and navigation methods, augmented and virtual reality applications, and ethical issues. Based on their work, we focus on a survey of indoor map data acquisition, modelling and presentation.

Indoor map data acquisition refers to the measurement techniques, sensors, media, and platforms used to acquire raw data of indoor environments [37]. Based on the measurement device configuration, commercial mobile indoor mapping systems can be classified into different groups: handheld; backpack and trolley [38] in indoor environments or human-based; wheel-based; boat-based; and sledge-based [39] in outdoor environments. The sensors used for 2D/3D indoor environment mapping usually consist of light detection and ranging (LiDAR), terrestrial laser scanner, RGB-D camera, inertial measurement units (IMUs), etc. Di Stefano et al. [39] present a comprehensive review of mobile laser scanning systems applied in both outdoor and indoor environments, grouped into five application domains: the built and urban environment, cultural heritage and archaeology, the underground environment, environmental monitoring, forestry, and agriculture. Virtanen et al. [40] present an approach for reconstruction of virtual indoor environments based on photogrammetry/image, terrestrial laser scanning, and depth camera, integrated with game engine to evaluate the quality and usability of geometric indoor models. Others have presented methods for searching the optimum location of the terrestrial laser scanner by using a genetic algorithm. For information acquisition of the environment based on mobile mapping systems, usually one or more sensors are used [36]. Simultaneous localization and mapping (SLAM) refers to building a map of the environment without any prior information and based on the data obtained from one or more sensors; it has been shown by the research community to be a robust technology for indoor mapping. Lluvia et al. [12] present a survey of major active SLAM methods as they relate to the robots used, the sensor from which the information is gathered, how the world is represented, the core concept of the contribution, the optimization objective, and where the test was performed. Chen et al. [41] present an accuracy comparison among three different SLAM-based mapping systems: Matterport, SLAMMER, and NAVIS in two different indoor scenes (an L-shaped corridor and an open style library). The results indicate SLAM-based indoor mapping systems with accurate LiDAR sensors can offer centimeter mapping accuracy in complex indoor environments. Point clouds acquired by laser scanners, depth cameras, and other sensors are a useful data source for the generation of 3D indoor models. Wu et al. [42] present a deep learning approach to automatically generate indoor spatial data by parsing floor plans, which is time-saving and relatively low cost.

Indoor modelling refers to the process supported by various tools and technologies involving the generation and the management of digital representations of the physical and the functional characteristics of indoor spaces; indoor maps can be regarded as the output of indoor surveying; and modelling and representation are the foundation of most indoor-based applications. Thereby, with the rapid development of smart cities, digital twins, and the metaverse, there is an increasing need for accurate and up-to-date spatial information and 3D building models of indoor environments. Recently, the ISPRS Working Group IV/5 initiated a benchmark standard on indoor modelling to evaluate and to document the performance of indoor modelling methods. The results are based on six-point cloud datasets for different indoor environments as captured by different sensors. Eleven submitted models are analyzed in [43]. Early surveys on indoor spatial models was done in [44], which from a context-aware perspective introduced cell-based, boundary-based, set-based, and graph-based models based on the requirements of localization, context-aware and adaptive navigation, location-aware communication, activity-oriented interactions, and spatial and behavioral analyses, as well as other efficiency-related requirements. As expected, hybrid spatial models that integrate different coexistent indoor space models combine the advantages of different models and thus effectively fulfill context-aware application requirements. Geographic information systems (GIS), which is designed to acquire, organize, manage, analyze, and visualize spatial data, can undoubtedly be used to study indoor modelling [9]. As well as visualization, indoor cartography or indoor map representation provide abstractions of the physical spaces based on indoor modelling and applications. A systematic review focused on the utilization of GIS in the analysis of indoor spaces was presented in [45]. Building information modeling (BIM), which aims to develop a methodology to manage essential building design and project data in digital format throughout the building's life-cycle [46], and 3D city models, which aim to represent urban environments with three-dimensional geometries of buildings and structures [47], are widely extended to indoor space modelling [48–51]. Recently, indoor space modelling has benefited from augmented reality (AR) technologies for indoor scenes; and, the use of AR devices, such as the Microsoft HoloLens, now enhances the indoor navigation experience [52,53].

With the development of IMM technologies and data quality improvement, for now, indoor mapping and modelling solutions are experiencing a real revolution, thus many modeling standards and file formats, such as IFC, MDR, CityGML, and IndoorGML emerged [54]. We will further discuss these modelling standards later.

2.3. *Standards for Indoor Positioning, Mapping and Navigation*

In this sub-section, we will introduce a series of standards for indoor positioning, and navigation and mapping, including the International Organization for Standardization and the International Electrotechnical Commission (ISO/IEC) Information technology—Real Time Locating Systems (RTLS), ISO Technical Committee (TC) 204 Intelligent Transport System (ITS), IEEE standard for robot Map Data Representation (MDR), ISO TC211 Geographic Information standards, Open Geospatial Consortium (OGC) standards for spatial data encoding and exchanging, and Industrial Foundation Classes (IFC) of buildingSmart.

2.3.1. ISO/IEC RTLS

The RTLS are systems with the ability to locate the position of a device anywhere in a defined space at any time. There are many situations and applications calling for RTLS. Rácz-Szabó et al. [55] provided a comprehensive overview of the application and the development possibilities of RTLS in the manufacturing field.

The ISO/IEC JTC 1/SC 31 (Joint Technical Committee 1, Information Technology Subcommittee) developed a series of international standards in the field of automatic identification and data capture techniques, including ISO/IEC 24730, ISO/IEC 24769, ISO/IEC 24770 and ISO/IEC 18305.

Standard ISO/IEC 24730 defines a single application programming interface (API) and three air interface protocols for RTLS. Standard ISO/IEC 24730-1:2014 [56] provides an API which defines a boundary across which application software uses the facilities of programming languages to collect information contained in RTLS tag blinks received by the RTLS infrastructure and enables software applications to utilize a RTLS infrastructure to locate assets with RTLS transmitters attached to them. The other three air interface protocols are:

1. Based on a direct sequence spread spectrum (DSSS), ISO/IEC 24730-2 defines a networked location system that provides X-Y coordinates and data telemetry, and it is comprised of this main document [57] and two additional components, that is ISO/IEC 24730-21:2012 [58], which specifies transmitters operating with a single spread code and employing a differential binary phase shift keying (DBPSK) data encoding and binary phase shift keying (BPSK) spreading scheme and ISO/IEC 24730-22:2012 [59], which specifies the air interface for a system that locates an asset in a controlled area.
2. Standard ISO/IEC 24730-5 [60], based on a chirp spread spectrum (CSS) technique, defines an air interface protocol which utilizes CSS at frequencies from 2.4 GHz to 2.483 GHz. This protocol supports bidirectional communication and two-way ranging between the readers and tags of an RTLS.
3. The ISO/IEC 24730-6 UWB air interface protocol is also comprised of two parts: ISO/IEC 24730-61:2013 [61] defines the physical layer (PHY) and tag management layer (TML) of an UWB air interface protocol that supports one directional simplex communication readers and tags of an RTLS that operate within the 6~10.6 GHz unlicensed band; and ISO/IEC 24730-62:2013 [62] defines the air-interface for RTLS using a physical layer UWB signaling mechanism (based on IEEE 802.15.4a UWB) with high rate pulse repetition frequencies (PRF) of 16 MHz or 64 MHz.

Device conformance test methods are specified in ISO/IEC 24769, which consists of four parts, namely ISO/IEC 24769-2:2013 [63], ISO/IEC 24769-5:2012 [64], ISO/IEC 24769-61:2015 [65], and ISO/IEC 24769-62:2015 [66]. These standards contain the measurements required to be made on a product to establish whether it conforms to the corresponding part of ISO/IEC 24730, and to define the test methods for determining the conformance of RTLS tags or/and readers with the specifications given in the corresponding subclauses of ISO/IEC 24730-2, ISO/IEC 24730-5, ISO/IEC 24730-61, and ISO/IEC 24730-62, respectively.

Test methods for measuring the performance of equipment compliant with ISO/IEC 24730 are specified by ISO/IEC 24770, which correspondingly consists of four parts, namely ISO/IEC 24770:2012 [67], ISO/IEC 24770-5 [68], ISO/IEC 24770-61:2015 [69], and ISO/IEC

24770-62:2015 [70]. These standards define the test methods measuring the performance of equipment compliant with ISO/IEC 24730-2, ISO/IEC 24730-5, ISO/IEC 24730-6, and ISO/IEC 24730-62, respectively.

On the other hand, ISO/IEC 18305:2016 [71] provides a standard methodology for evaluating indoor localization systems and detailed test and evaluation procedures, performance metrics, and scenarios for localization and tracking systems. Potorti et al. [72] gave detailed comments on different scenarios for performing tests, the overall framework, common evaluation criteria, standardized methodologies, test and evaluation procedures, and performance metrics. The authors also analyzed compliance with the standard of IPIN and Microsoft indoor localization competitions.

2.3.2. ISO TC204 ITS

According to Mordor Intelligence [73], ITS is the application of sensing, analysis, control, and communications technologies in transportation in order to improve safety, mobility, and efficiency, and it refers to the advanced technologies that are being applied to vehicles, infrastructure, and operating systems, which make the vehicles intelligent. The intelligent transport systems market was valued at USD 22.88 billion in 2020, and it is expected to reach a value of USD 30.65 billion by 2026, at a CAGR of 5.11% over the forecast period (2021–2026) [73]. Thus, many ITS standards were developed by SDOs to satisfy the fast-growing ITS application and service requirements. Early in 2000, the Joint Program Office (JPO) of the U.S. Department of Transportation (DOT) asked the National Research Council's (NRC's) Transportation Research Board to undertake a review of JPO's ITS Standards Program [74] and the reviewers presented their views and shared their experiences with the ITS Standards Program.

Since ITS is a very complicated ecosystem that comprises humans, vehicles, and the backbone network, many standardization bodies are continuously working on the development of standards and protocols that define how ITS components must communicate with one another [75]. Williams [76] presented a detailed list of ITS standards that were developed before 2008, and his book can be used as a reference of standards in the ITS sector. Nevertheless, none of standards in the list was intended for the indoor space. With the spread of mobile devices such as smart phones, and consequently the massive demands of various indoor navigation-based applications, several indoor navigation standards for ITS have been published, including ISO 17438.

The ISO 17438 standard provided the documents and the references required to support the implementation of indoor navigation, consisting of four parts under the general title Intelligent transport systems—Indoor navigation for personal and vehicle ITS station.

The ISO 17438 Part 1 standard [77] specified the indoor navigation system architecture, use cases, and requirements in providing indoor navigation to various types of users. The architecture follows the existing ITS communication architecture with four additional components. The indoor data server component generates and provides indoor map data and indoor positioning reference data, the indoor data server registry component in the central ITS station manages metadata for indoor map data; the indoor positioning infrastructure component facilitates indoor localization; and the indoor navigation function module component in the P/V ITS station provides navigation functionality. Applications supporting indoor navigation for personal and vehicle ITS stations need to obtain indoor map data and positioning reference data.

Parts 2 and 3 of ISO 17438 are under development. Part 2 is planned to specify requirements and specification for indoor map data format and Part 3 is to specify requirements and specification for indoor positioning references data format. Part 4 of ISO 17438 [13] defined use cases, requirements, and message specifications for supporting indoor navigation in intelligent transport systems.

Besides ISO 17438, several ITS standards can also be used as a reference for indoor navigation applications and services. The ISO 17267:2009 standard [78] specified an application programming interface (API) for ITS navigation, including a set of function calls, access interface, the data that may be retrieved from the map database, and application examples. The ISO 14825:2011 standard [79], which specified the conceptual and logical data model and physical encoding formats for geographic databases for ITS applications and services, has been replaced by ISO 20524-1:2020 [80] and ISO 20524-2:2020 [81]. The GDF5.1 is an evolution of GDF5.0 that introduces the concept of sharable features, cooperative ITS and public transport. The data model and encoding formats may be adapted for indoor map data representation.

2.3.3. OGC CityGML and IndoorGML

In the last decades, 3D city models have been used in dozens of application domains for diverse purposes, such as urban planning, facility management, 3D cadaster, energy demand estimation, aiding positioning and navigation, and emergency response, etc. [47]. CityGML is an open encoding standard of the Open Geospatial Consortium (OGC) for representation, storage, and exchange of semantic 3D city models based on the Geography Markup Language version 3.1.1 (GML3) [82]. Over a decade of development, CityGML is generally considered as the most internationally widespread open reference standard for 3D city model management, storage, and exchange, partly because of its characteristics, such as [82]:

- Modularization

The CityGML data model is thematically decomposed into a core module and thematic extension modules. The core module comprises the basic concepts and components of the CityGML data model, and based on the core module, each extension covers a specific thematic field of virtual 3D city models. CityGML 2.0 introduces 13 thematic extension modules, i.e., Appearance, Bridge, Building, CityFurniture, CityObjectGroup, Generics, LandUse, Relief, Transportation, Tunnel, Vegetation, WaterBody, and TexturedSurface. These modules contain one or more classes representing specific types of objects, and the most used module in practice is the Building module [83].

- Application Domain Extensions (ADE)

Even though CityGML modularization provide a mechanism to extend core module, the advent of dozens of applications still requires some additional information that is not readily available in the CityGML data model, but it is beyond the scope of current standard version. Thereby, one of the significant requirements is to specify extensions to the existing CityGML data model. Basically, there are two ways to support augmenting the CityGML data model: through extending generic objects and attributes, and mainly using the ADE mechanism [84]. The ADE mechanism is orthogonally aligned with the modularization approach in CityGML, but it has to be defined in an extra XML schema definition file with its own namespace. Two examples for ADEs (i.e., Noise Immission Simulation and Ubiquitous Network) are included in the CityGML 2.0 standard [82]. Biljecki et al. [84] presented a survey of many more ADEs developed for a variety of purposes.

- Multi-scale modelling

CityGML supports five different levels of detail (LOD), that is, level LOD0 is essentially 2.5D Digital Terrain Model (DTM) over which an aerial image or a map may be draped; LOD1 is the well-known block model comprising prismatic buildings with flat roof structures; building in LOD2 has differentiated roof structures and thematically differentiated boundary surfaces; LOD3 denotes architectural models with detailed wall and roof structures potentially including doors and windows; while, LOD4 completes a LOD3 model by adding interior structures (for example, rooms, interior doors, stairs, and furniture) for buildings [82]. Each object in CityGML can have a different representation for every LOD, thus making possible efficient visualization and data analysis to meet different application requirements.

- Other characteristics

Other characteristics of CityGML are introduced in [82], including coherent semantical-geometrical modelling, closure surfaces, Terrain Intersection Curve (TIC), code lists for enumerative attributes, external references, city object groups, appearances, prototypic objects/scene graph concepts, and generic city objects and attributes. For example, semantical-geometrical modelling is one of the most important design principles for CityGML as real-world entities are represented by features with geometry and attributes, as well as relations and aggregation hierarchies between features.

Although the CityGML LoD 4 is capable of describing indoor objects such as ceilings, windows, doors, furniture, etc., and indoor ADE can include indoor space features and indoor facility features for indoor facility management [85], the OGC IndoorGML standard aims to support location-based services for indoor navigation; however, CityGML has some missing elements for indoor applications, particularly indoor navigation. In this respect, indoorGML is a complementary standard to CityGML, KML, and IFC [86]. Based on GML 3.2.1, IndoorGML provides a cellular and structured space model, which supports semantic, geometric, topological, and multi-layered representation of indoor environments. While the basic concepts of IndoorGML are discussed in detail in [87,88], Ryoo et al. [11] presented a comparison between CityGML and IndoorGML; and, Kim et al. [89] discussed the issues on the integration of IndoorGML and CityGML LoD 4 by two methods: automatic derivation of IndoorGML data from CityGML LoD 4 data set and external references from IndoorGML instance to an object in CityGML data. Future changes and improvements are being considered in the IndoorGML2.0 standard proposal [90].

2.3.4. IEEE MDR

The requirements raised by robot navigation tasks in 2D indoor and outdoor environments may include: map quality in terms of metric accuracy, probabilistic behavior of robot navigation, and capability of handling metric and topological maps [91]. In order to satisfy robot navigation requirements, the IEEE Robotics & Automation Society (RAS) developed a standard for Robot Map Data Representation (MDR) for navigation, which specified data models and data formats for two-dimensional (2D) metric and topological maps.

The IEEE 1873–2015 standard defines a global map concept, considered as a tree consisting of a collection of 2D local maps. The local map, which is either a metric or a topological map, is represented by nodes and arcs, where nodes represent local maps and arcs represent the relations (for example, transformation of coordinate system) between two local maps. A metric map may contain grid maps and geometric maps, where a grid map decomposes the representation of an environment into square cells that constitute atomic pieces of information, and a geometric map comprises a list of continuous geometric features. A topological map represents an environment in the form of a graph consisting of a set of nodes and edges connecting them [92]. This standard also specifies the XML implementation according to this data model. More information about the XML data format in practice can be found in [91,92].

2.3.5. IFC of BuildingSMART

The Industry Foundation Classes (IFC), originally the buildingSMART open standard for BIM, has been adapted as the ISO 16739 international standard (ISO 16739-1:2018 [93]), which specifies a data schema (represented as an EXPRESS schema) and an exchange file format structure. The exchange format consists of definitions that are required during the life cycle phases of buildings and that are required by the various disciplines involved within the life cycle phases. The IFC includes several hundred entity classes in an entity-relationship model, which supports the semantic description and geometric representation of typical construction elements and their relationships.

Supported by the GeoBIM benchmark project, Noardo et al. [94] presented a specific study of the interoperability of the IFC standard, testing 33 software packages that support the IFC and focusing on the themes of georeferencing, semantics, and geometry. The general functionalities include visualization, editing, query, analysis, and export possibilities, and so on. However, the authors did not comment on the applicability of the IFC standard for indoor map representation and navigation. Liu et al. [49], however, presented a survey of indoor navigation approaches, applications, and solutions supported by IFC. These survey results indicate that the most active research direction is to generate the navigation models from IFC data. Another group of researchers have investigated the transformation from IFC to other different data models and their integrations. For example, Lim et al. [95] presented a graph transformation approach from IFC to CityGML, Linet al. [96] introduced a method to cope with path planning for 3D indoor space through an IFC file as input, and Gilbert et al. [97] discussed some of the problems that occur when integrating three built environment standards: CityGML, IFC, and LandInfra.

2.3.6. Other Standards and Formats

Besides these standards for indoor positioning, mapping, and navigation, several other standards and formats are also relevant to indoor applications, including the OGC Land and Infrastructure standard (LandInfra) aimed at land and civil engineering infrastructure facilities representation [98]; the green building data model (gbXML) (https://www.gbxml.org, accessed on 3 March 2022) aimed at the representation of buildings for energy analysis; the Indoor Map Data Format (IMDF), published by Apple and OGC, that provides the definitions of selected indoor feature types and certain venue types such as airports, malls, and train station based on GeoJSON [99]; the OSM for indoor environments [100], and so on.

Hopefully, a group of ISO TC211 Geographic Information standards, which specify methods, tools, and services for geographic data management, acquisition, processing, analysis, access, and presenting and transferring geographic information between different users, systems and locations, may be extended and utilized in indoor environments, for example:

- ISO 19116:2019 Positioning services, which specifies the data structures and contents of an interface between position-providing device(s) and position-using devices(s) so that position information can be interpreted unambiguously.
- ISO 19133:2005 LBS—Tracking and navigation, which describes the data types, and operations associated with those types, for the implementation of tracking and navigation services.
- ISO 19134:2007 LBS—Multimodal routing and navigation, which specifies the data types and their associated operations for the implementation of multimodal location-based services for routing and navigation.
- ISO 19147:2015 Transfer Nodes, which specifies the data types and code lists associated with those types for the implementation of transfer nodes and their services in transport modelling and location-based services.

3. Requirements and Architecture of IPMN Standards System

Although research on indoor positioning, mapping, and navigation show great advances over the past two decades, as observed from literature, there are still several technical and non-technical challenges in the development of LBS, including indoor positioning, availability of indoor maps, and location privacy [4]. In terms of positioning technologies, reliable, accurate, inexpensive, seamless, indoor/outdoor positioning is needed for many LBS applications, particularly concerning safety and security applications, which are potentially life-saving such as emergency services. For indoor maps, issues such as the complexity for modeling and analysis, contextual information inference, data storage, and streaming, together with privacy concerns comprise quite a challenge considering map coverage and availability of the content [4].

The biggest challenge is lack of standardization [5], even though several IPMN standards have been published, as mentioned previously. In particular, there is no standard that can serve as a guide for designing localization and proximity techniques [5]. Current IPMN standards have been developed by various SDOs for specific purposes; for example, ISO 17438—developed by ISO Technical Committee (TC) 204—identifies the requirements and use cases for ITS navigation, and they do not specify either indoor positioning technologies and reference data or indoor map formats. Furthermore, the requirements and use cases may vary from one application (for example, safety and security applications) to another (for example, ITS or assets management).

From the perspective of IPMN standards and system theory, this paper focuses on the re-thinking of the IPMN standards system. First of all, we need to study the basic information theories, concepts, and models behind the existing and emerging IPMN technologies, asking for instance, such as what is the underlying theory of IPMN? Secondly, from the viewpoint of engineering, can current technologies, standards and systems meet the requirements of most applications? And finally, what can we do to tackle the IPMN problem in the coming years? Therefore, regarding the whole process of IPMN, which includes positioning equipment deployment, indoor map data acquisition and organization, indoor and outdoor seamless positioning and navigation services, and testing and evaluation, we summarize the IPMN requirements as follows.

1. Positioning device deployment. Indoor positioning technology can be divided as one requiring external equipment and the other, device-free. When utilizing external equipment, such as WIFI, as positioning method, deployment of equipment in indoor scene is needed in advance. Standardization in this stage is required in choosing a deployment method and the equipment and testing method suitable for indoor environments.
2. Indoor map data acquisition and organization. Indoor positioning cannot be separated from the visualization of indoor scenes. First, indoor map data models must be built to express indoor scenes explicitly. Second, standards for data acquisition and organization are required because indoor maps are usually limited by wireless network transmission rates and mobile network terminal resolution. In addition, map visualization of large-scale indoor spaces should consider the expression of symbols, color, and semantic information, which also needs relevant standards.
3. Seamless indoor and outdoor positioning and navigation services. In large-scale applications, only indoor positioning is not of practical significance. When the environment of pedestrians switches from indoors to outdoors, the corresponding location method, map data, and coordinate system should be switched accordingly, meaning that there must be provision of standards for these transformations. For the final development of an integrated multi-mode indoor positioning systems, software and related protocol standards are required. To achieve navigation, standards for navigation models are a requirement.
4. Testing and evaluation. The last stage is testing and evaluating accuracy and cost of positioning technologies. A consistency test is also required for software development. Both of the tests should have standards as guidance.

Based on these considerations, in this paper, we propose a standard system architecture, composed of four layers: the basic general layer, the data layer, the application layer, and the environment and software layer. As shown in Figure 2, the general class includes terms, pattern language, reference models, coordinate reference system, and consistency test. The data sources class includes metadata, indoor map data acquisition, data models, resource catalog, database building and updating. the application service class includes information transmission and exchange, visualization, SDK interface, services, and products. The environment and tools class includes deployment of positioning infrastructure and software. The standard system will intersect, coordinate, and share with other related standard systems, such as RTLS, surveying and mapping geographic information standards and smart city standards.

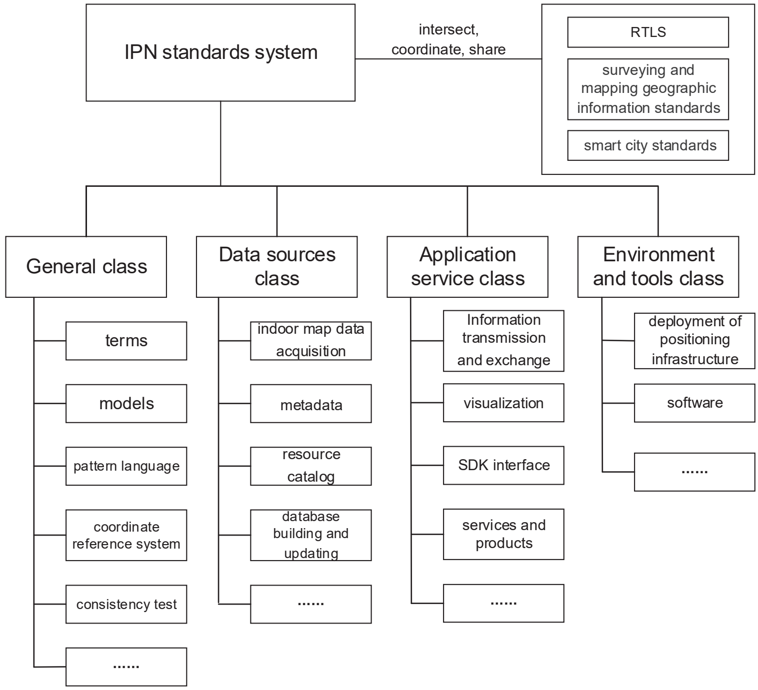


Figure 2. Standard system architecture.

In this architecture, there are inertial connections between each class. For example, visualizations in an application service class should be based on the data model in the data sources class. The basic general class is the basis of this system framework, and the data sources class and application service class are the main body of this standard system. The environment and tool class provide guarantees for the three classes. To improve the rationality, coordination and integrity of the system, some of the standards are strengthened on the basis of existing standards.

At the present stage, we provide a hybrid indoor positioning system architecture, two draft standards for the indoor map models, core information models, and navigation information standards, detailed in Section 4.

4. Our Research on IPMN Standards

Although there are IPMN standards developed by different SDOs, the new indoor positioning, mapping, and navigation technologies, such as 5G, IoT, smart cities and digital twins, IPS is continuously evolving. Our work was focused on the indoor intelligent hybrid positioning and GIS technology with high availability and accuracy project, which began in the year of 2016 and it is supported by the National Key Research and Development Program of China. The goal of our research is to design a hybrid indoor positioning system architecture, develop IPMN standards, and integrate various indoor positioning technologies and GIS.

4.1. Hybrid Indoor Positioning System Architecture

Our IPMN system architecture, as shown in Figure 3, is very similar to the indoor navigation architecture for ITS. Typically, an IPMN system contains a backend layer, which represents different servers in the cloud computing environment, and a client layer, which represents the applications for smartphones or mobile robotic devices. Large data, such as static indoor map data, positioning fingerprints database, containing all kinds of information (sensors, energy efficiency, etc.) about smartphones, and so on, should be stored on the backend side and should be updated frequently. The client can download needed data when it generates coordinates or runs a path-finding algorithm using various positioning and GIS technologies. Sometimes, a client needs to update the device location to the server for monitoring or tracking services. The key characteristic of our architecture is that the GIS technologies, and functionalities such as semantic analysis, are integrated into the individual positioning technology for enhanced accuracy and reliable positioning.

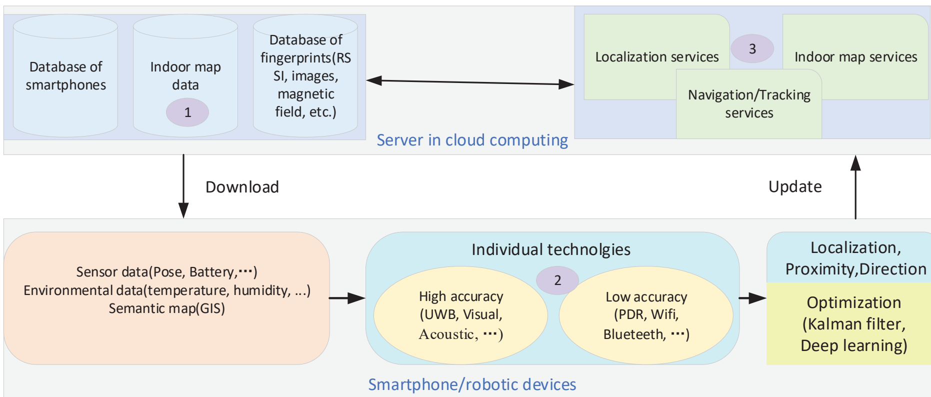


Figure 3. A GIS integrated hybrid indoor positioning system architecture.

In this paper, we discussed the standards for the architecture. We classified the standards used in this architecture into three parts:

1. Standards for indoor map data.
2. Standards for positioning technologies.
3. Standards for navigation service.

In the following sub-section, we will briefly discuss some standards used for our project, including the:

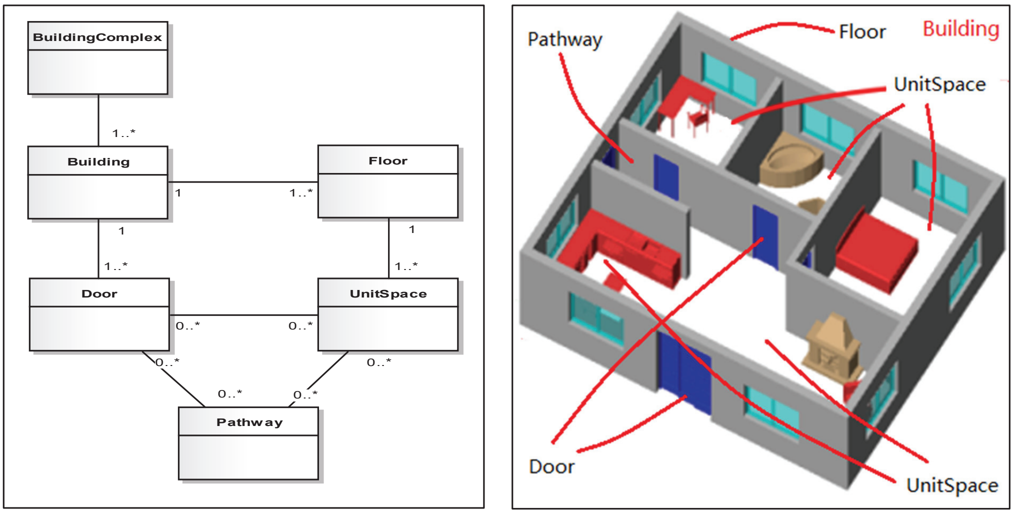
- Content model for indoor mapping.
- Data collection for indoor maps.
- GIS model for indoor spatial data.
- Indoor map symbols.
- Specification for digital indoor map products.
- Multi-source fusion positioning data interfaces.
- Seamless cooperative positioning service interfaces.

4.2. Standards for Indoor Map Data

4.2.1. Content Model for Indoor Mapping

High-accuracy indoor map data plays an important role in the indoor navigation applications, for example, some positioning technologies can use the semantic information from indoor maps to correct the accumulated location bias, so many standards have been developed to specify the map data collection procedures and methods, data formats, data models, representations and symbology, web map services, etc. Indoor map data can be collected using SLAM, Lidar, traditional total station survey, or automatically produced from CAD building drawings and floor plan images. However, we first need to determine the elements that should be contained in the indoor map for a specific application. This led to a standard entitled the "content model for indoor mapping," which specifies the basic conceptual, content, and topological models for indoor mapping. The purpose of this standard is to provide common understanding and sharing of indoor map data content for indoor map elements when collecting data, creating database, and modeling spatial relationships.

The conceptual model for indoor mapping can be described by the terms BuildingComplex, Building, Floor, Door, UnitSpace, and Pathway, as shown in Figure 4. BuildingComplex usually corresponds to a large area of interest, consisting of heterogeneous buildings. The concept of building is straightforward and comprehensive.



(a) (b)

Figure 4. Conceptual model of indoor map. (**a**) elements and their relationships of indoor map, (**b**) an illustration of building element.

Based on the conceptual model for indoor maps, the content model is given in the form of UML, as in Figure 5, which specifies the content and mandatory attributes required to describe an element in a building. However, the basic information may be inadequate for some navigation or tracking applications. Under these circumstances, users can extend the content model, for example, a navigation information model can be derived from navigation application scenarios, as shown in Figure 6.

Some specifications matching the content model were also developed in our project, including (1) specification for data collection of indoor maps—Part1: floor plan, (2) specification for GIS model of indoor spatial data, (3) indoor map symbols for general geospatial elements, and (4) technical specifications for digital indoor map production.

4.2.2. Data Collection for Indoor Maps

Several methods, such as SLAM, Lidar, and traditional total station surveys can be used for data collection of indoor maps. Indoor maps can also be produced automatically at low cost by extracting indoor elements from the existing floor plans, which are usually in the format of CAD drawings. This specification presents a procedure and detailed techniques to obtain digital indoor maps from existing floor plan, as shown in Figure 7.

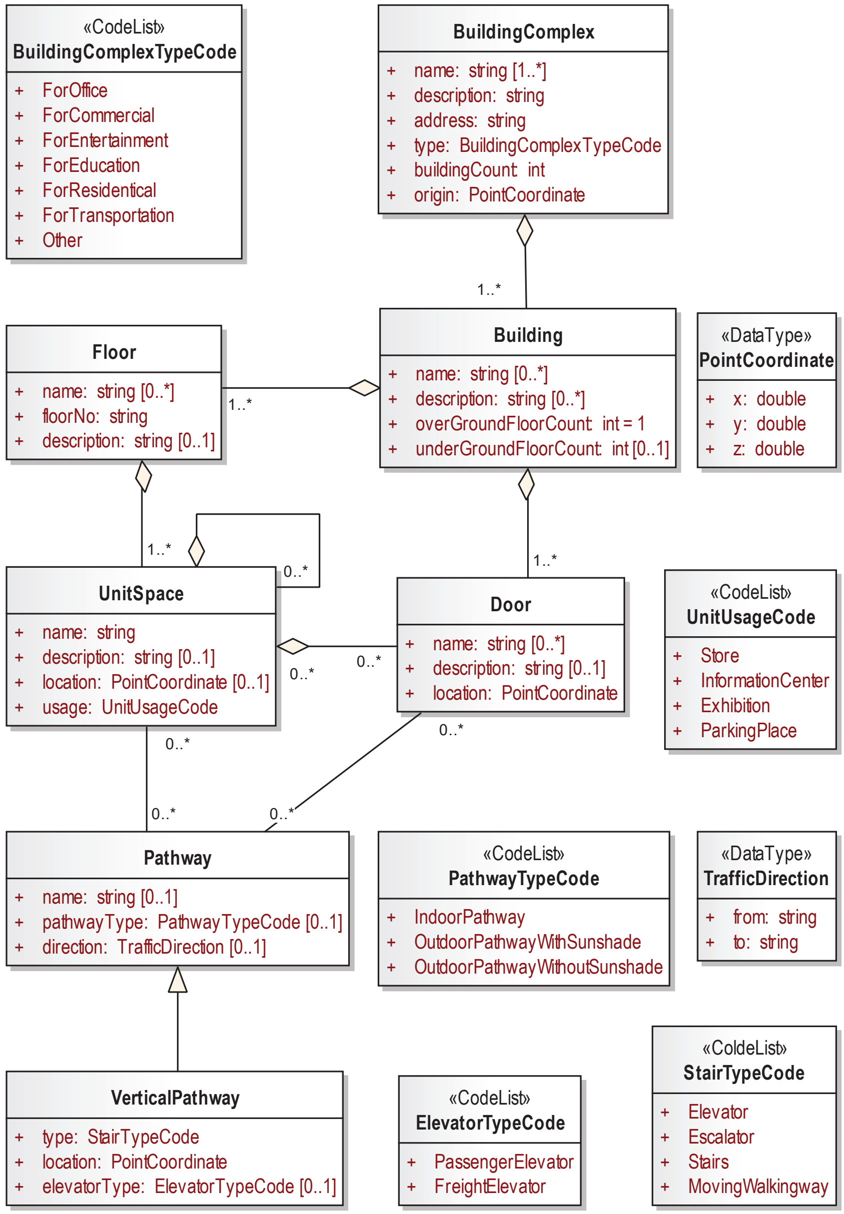


Figure 5. Content model of indoor map—Core Information Model.

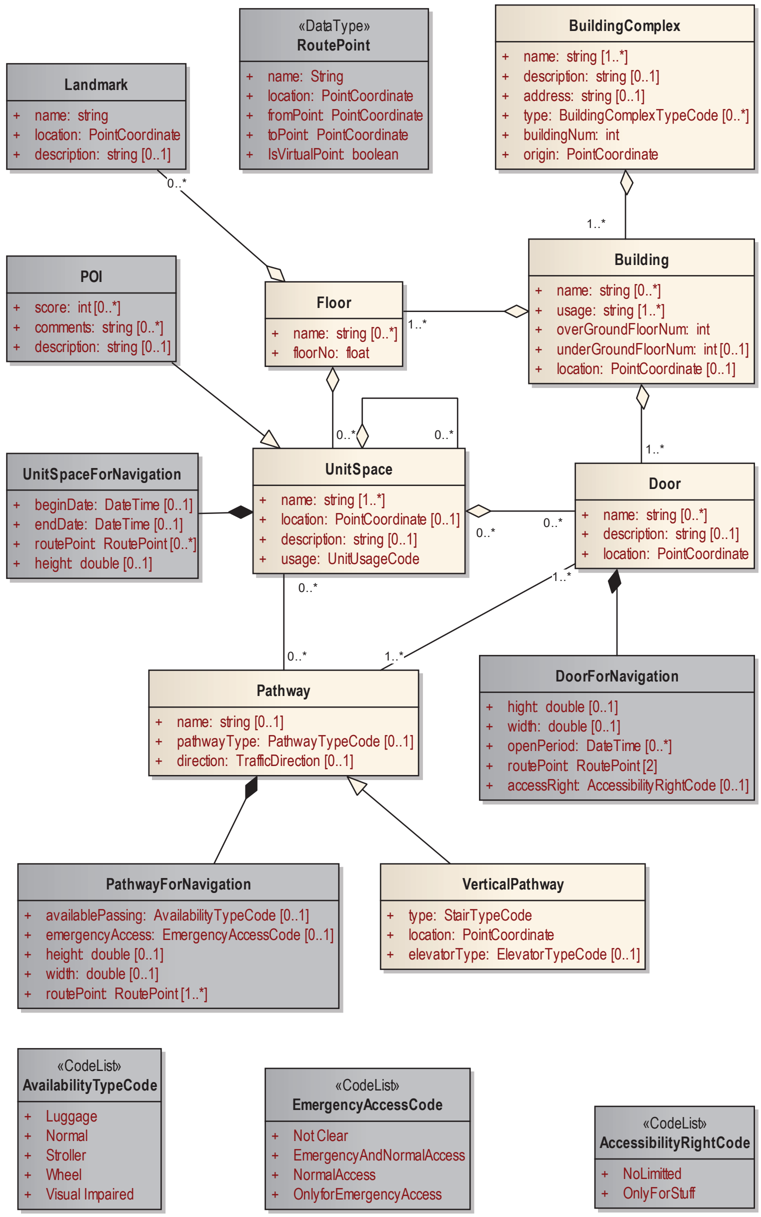


Figure 6. Content model of indoor map—Navigation Information Model.

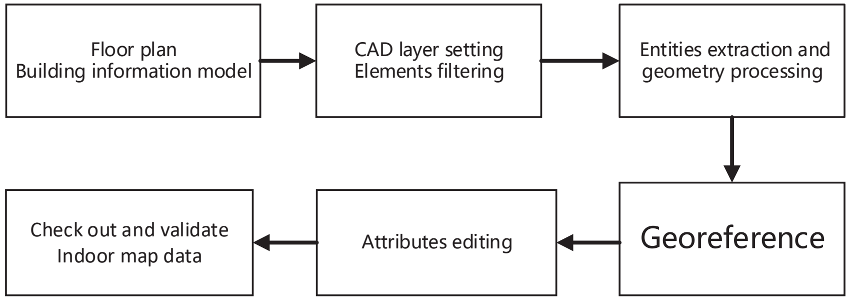
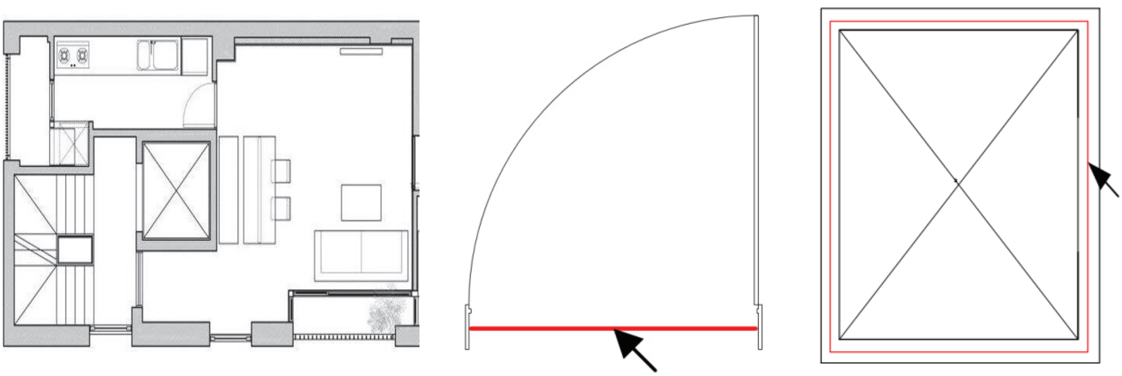


Figure 7. Procedure of digitalizing indoor map from existed floor plan.

The key process in Figure 7 is entity extraction and handling element geometry with a priori knowledge. Figure 8 shows some examples of element geometry extraction.



(**a**) (**b**) (**c**)

Figure 8. Examples of element geometry extraction. (**a**) original floor plan, (**b**) door geometry extraction, (**c**) vertical pathway geometry extraction.

This approach can quickly generate indoor maps in accordance with a content model at very low cost, especially in the scenarios where indoor surveying is prohibited.

4.2.3. GIS Model for Indoor Spatial Data

Although GIS models and spatial analysis are widely used in outdoor settings, there are some limitations for indoor GIS due to complicated and isomeric structures of indoor elements. This specification frames the indoor GIS model, which is somewhat different from the existing GIS model in terms of data organization, management, and representation. Figure 9 shows the basic indoor GIS model, which mainly consists of three parts. Firstly, indoor spatial data are organized and managed according to the content model, each core element is grouped or classified into logical layers. Secondly, the geometry representation should support 2D, 2.5D, and 3D coordinates, and furthermore, time or dynamic properties of elements should be considered for spatiotemporal analysis. Indoor spatial data can be stored, transferred or exchanged with MDR, Indoor GML, and other indoor map data formats. Lastly, topological relationships can be derived from the geometry data or cached for immediate pathway finding. From an overall view, this GIS model for indoor spatial data conforms with those for outdoor data, however, the existing commercial or open-source GIS software hardly supports indoor spatial data.

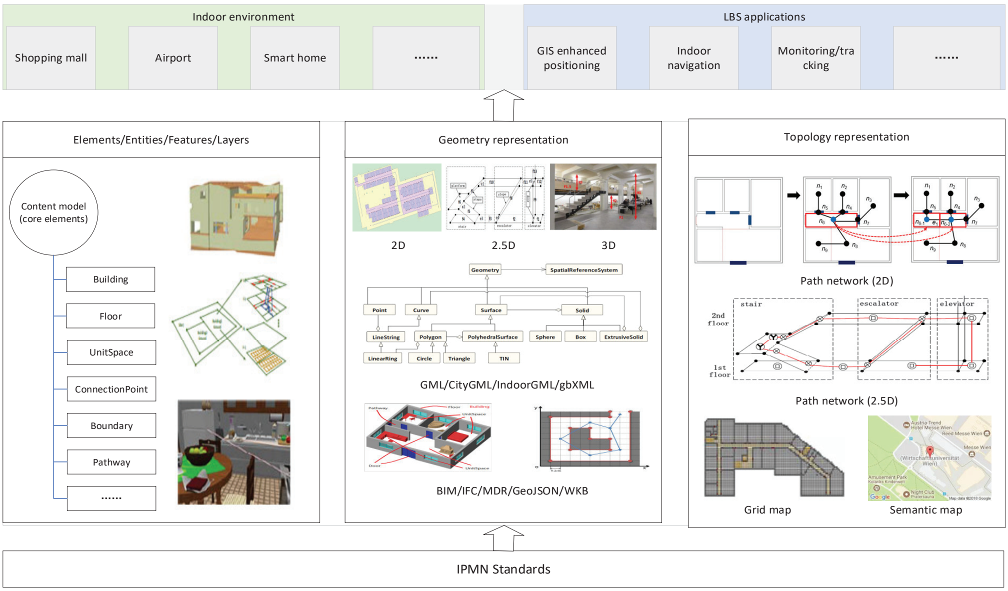


Figure 9. GIS model of indoor spatial data.

4.2.4. Indoor Map Symbols

This specification provides symbols, labels, styles and rules used for indoor maps, and easily understood. So, we merely list some symbols in Table 1.

Table 1. Examples of indoor map symbols.

Code	Name	Symbol
A.1.1	exit	
A.1.4	stair	
A.1.5	elevator	
A.1.6	escalator	

Table 1. *Cont.*

Code	Name	Symbol
A.2.5	parking	
A.4.1.3	ATM	

4.2.5. Specification for Digital Indoor Map Products

This specification determines how indoor maps can become authorized digital indoor map production, public or government assets. It specifies the basic requirements for indoor map products, just like traditional digital outdoor map products, such as Digital Line Graphic (DLG) products.

4.3. Multi-Source Fusion Positioning Data Interface

This kind of standard specifies the data interface among positioning engines. Usually, there are two kinds of positioning engines, one is the main engine, which integrates positioning results from different technologies, and the others are called sub-engines. Each sub-engine involves typically an individual technology, as illustrated in Figure 10.

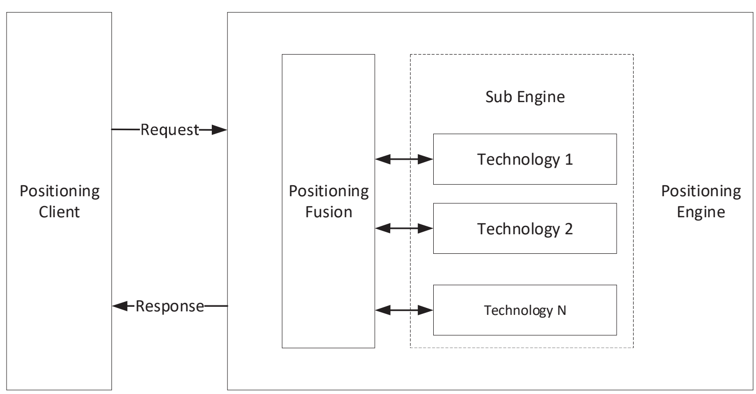


Figure 10. Multi-source fusion positioning data interface (From GB/T 38630-2020, [101]).

The protocol for information exchange between two engines is based on request/response mechanism, but not specified with concrete protocols in this standard; however, both the sensor data and the positioning results are specified in detail.

Related standards specified the data structure, format, type, and etc. of individual positioning technologies, such as GB/T 38627-2020 [102], specify the magnetic positioning data interface. Other indoor positioning standards, such as visual positioning data interface, protocols for information superposition based on ubiquitous location, and so on are planned or are under development.

4.4. Seamless Cooperative Positioning Service Interface

Based on the integrated hybrid indoor positioning system architecture (see Figure 3), the standard for indoor and outdoor multi-mode cooperative positioning service interface [103] can be used in some scenarios that applications need to get the device locations from the data server. This standard specifies the basic service elements and service interfaces for seamless collaborative positioning, and designed according to the OGC Web Services Common Standard [104] and specifies five operations as in Figure 11.

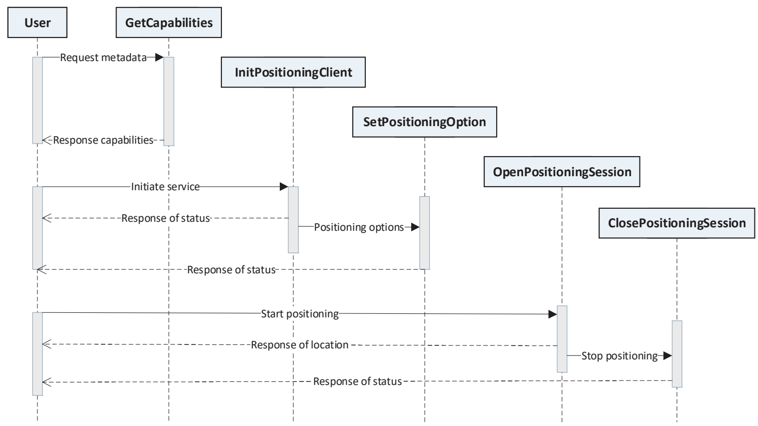


Figure 11. Sequence diagram of location service process (From GB/T 35629-2017 [103]).

For a localization system or service, the service should retrieve adequate information for applications, including the service provider, coordinate reference system, quality information, positioning technology type, and potential service exceptions. The service metadata is also specified in this standard, as detailed in Figure 12.

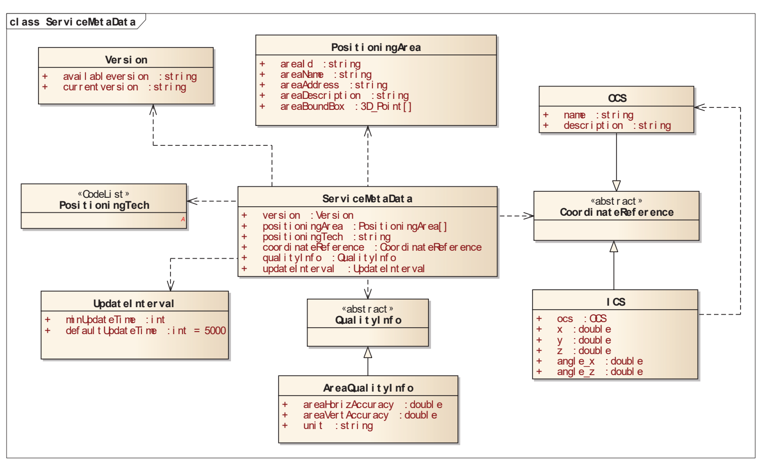


Figure 12. Metadata of cooperative positioning service.

Similarly, applications can get indoor maps or entities through the OGC WMS [105] or WFS [106] standards.

5. Conclusions

The emergence of indoor based applications and markets promotes advances in IPMN technologies and standards. Different techniques, technologies, mechanisms, methodologies, systems, platforms, and standards have been developed for indoor localization services and applications. However, IPMN applications still face several technical and non-technical challenges, such as quality of positioning service, availability of indoor maps, and location privacy. Currently there is no proposed solution that can satisfy all indoor application requirements. One of the biggest challenges is a lack of standardization. The existing IPMN standards published by different SDOs, such as ISO, IEEE, and OGC differ from each other, and they focus on different viewpoints of indoor positioning, mapping, and navigation, such as automatic identification and data capture techniques (RTLS), communications technologies in transportation (ITS), city and indoor models (CityGML and IndoorGML), building information model (BIM), and robot navigation (MDR).

This paper updates the review of indoor positioning and mapping technologies and standards. As we re-think the results, we present an architecture for IPMN, and standards based on the architecture for our project. We found by our project experience that the coordinate IPMN standards system needs to be formed from the concepts, models, and technologies to the industrial application schemas. Thus, we proposed several standards including hybrid indoor positioning, content model for indoor map, data collection, GIS model, symbols, and indoor positioning service. The main purpose here is to provide readers and researchers with guidance to IPMN technologies and standards; and, for standard developers to have a way to develop complementary standards to form the backbone for an integrated IPMN standards system.

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standards

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Review

Standards and Assessment of Construction Products: Case Study of Ceramic Tile Adhesives

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Abstract: This work attempts to draw attention to the importance of a multidimensional approach when creating standard requirements in the assessment of construction products with the example of ceramic tile adhesives (CTAs). CTAs are an essential group of building materials today, the continuous development of which has been noted since the 1960s. However, until 2001, i.e., the year when EN 12004 was published, there were no precise requirements for CTAs at the European level, which often made it difficult or, in extreme cases, even impossible to assess the product objectively. Under the provisions of EN 12004, for twenty years, the basis for the assessment and verification of constancy of performance (AVCP) of CTAs has been adhesion determined by tensile strength. The paper discusses the test methods, paying attention to their imperfections, including the impact of the materials used in measurements, i.e., concrete slab, ceramic tile, and water quality. The results of the multi-annual interlaboratory tests indicate that an essential factor that must be considered in the process of AVCP is test measurement uncertainty. Additionally, it should be remembered that uncertainty also occurs at other assessment levels. It also seems that the simple acceptance rule that does not consider the variability resulting from the measurement uncertainty is inadequate when assessing CTAs.

Keywords: ceramic tile adhesive; measurements uncertainty; assessment of construction products; tensile adhesion strength; market surveillance

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1. Introduction

The principles of the construction products market in the European Union are regulated by the Construction Products Regulation (CPR) [1]. CPR ensures the free movement of construction products within the EU, taking into account the interests and needs of the Member States. This document lays down harmonized rules for the CE marking of construction products and defines the method of declaring their performance with regard to the essential characteristics of construction products. The requirements set out in the CPR are necessary to ensure that reliable information is available to professionals, authorities, and consumers and to allow for the construction products to be compared between manufacturers in the different Member States. A fundamental part of the functioning of the EU market of products is standardization which facilitates the development and maintenance of common technical terminology. Standardization is a link between the requirements of the Member States and the Declaration of Performance (DoP) issued following CPR. The manufacturer prepares DoP for the user of the product. The European system of technical regulations created by CEN, CENELEC, and EOTA is a factor that stimulates competition and innovation while contributing to improving consumer safety and reducing the number of accidents, making European standards a global benchmark [2].

The foundations of standardization are consistency, transparency, openness, consensus, independence from special interests, and efficiency [3]. In principle, the European standards are driven by business and made through a balanced process involving relevant stakeholders. In the EU, standards support market-based competition and help to reduce costs [4]. European standardization is an integral part of supporting global competitiveness, and therefore, the aspect of cooperation with international standardization bodies, namely ISO, IEC, and ITU, is also essential.

The economic landscape of the EU and its international trading partners is still changing, taking on a rather dynamic character in some areas, and therefore it is crucial to adopt standardization processes to these changes. It is essential to consider the verified achievements of science and technology. In Strategy 2030, CEN and CENELEC intend to strengthen their position as independent facilitators between industry, regulators, consumers, and other stakeholders and to ensure that the European standards contribute to the competitiveness and sustainability of the European economy [5]. Recently conducted surveys have shown that the internal market and its functioning is a topic of interest, with stakeholders asking for better coordination from the EU and harmonization across the EU on building standards and overall demanding better regulation of the construction sector [6].

Construction is a branch of the economy and a scientific discipline with specific interrelationships and conditions between science and practice [7]. In construction, a vast number of various building materials are used, which impact the fulfillment of the basic requirements specified in the CPR. Every construction product must be assessed before it is placed on the market [1]. In the case of CE marking, the manufacturer is obliged to assess and verify the construction product's constancy of performance (AVCP) [1]. Due to the variety of construction materials and their intended use, the assessment is carried out at very different levels in countless laboratories worldwide. In theory, as a rule, measurement processes must be unambiguous so that metrologically consistent results are achieved when reproduced anywhere in the world. However, the reality is much more complicated, to mention the situation where the performance values of the product determined in the tests are close to the evaluation criterion. In such a situation, the manufacturer must be aware of the risk associated with the fact that in the control procedures of construction products placed on the market or during periodic inspections, his product may be considered as non-conforming [8]. For some construction products, assessment is more complex due to the products' nature which requires appropriate preparation before use, e.g., mixing with water. For this reason, assessment by market supervision authorities is also multifaceted, i.e., the formal assessment of the DoP and testing of samples of products taken from the market. For this reason, it is crucial to answer the following question: To what extent is the assessment of a construction product based on tests reliable [9]. Another dimension of product evaluation is the relationship between the results of laboratory tests and the actual behavior of the product during its subsequent use, especially in the case of construction materials for which destructive testing methods are used. In the case of using semi-destructive methods to assess construction products and especially non-destructive testing methods, the situation is less complex. For this reason, there has been a significant development of non-destructive testing in recent years for the evaluation of materials in civil engineering. [10]. All the accounts mentioned above present quite a scientific challenge. It is impossible in the EU system with CE marking to carry out the product assessment process without knowing the requirements specified in the harmonized standard or the European Technical Assessment [1].

This review overviews the changes in the assessment and verification of the performance of ceramic tile adhesives (CTAs) in the EU over the past twenty years. Due to the dominant market share of cementitious CTAs, these adhesives constitute the subject of a detailed analysis of the three types of CTAs. Following the requirements of the EN 12004 standard established in 2001, the basis for the assessment and classification of cementitious CTAs is adhesion, which is determined by the tensile strength and the open time determined by adhesion strength after a given time after which the ceramic tile is embedded. The paper presents the measurement methods in detail and discusses their imperfections, including the impact of the materials used in measurements, i.e., concrete slab, ceramic tile, and water quality. The results of many years of interlaboratory comparisons (ILCs) and conclusions from laboratories and producers of CTAs are discussed. It has been pointed out that the knowledge of uncertainty, particularly on the uncertainty resulting from tensile adhesion strength measurement uncertainty (MU), is fundamental when assessing product compliance. The activities of construction supervision authorities in the field of CTAs collected from the market and the conclusions drawn from them for a possible amendment of the requirements and test methods specified in EN 12004, taking into account the achievements of science and technology in the past twenty years, are discussed.

2. Ceramic Tile Adhesives and Their Importance in Construction Today

When discussing CTAs, it should be noted at the outset that there are three types of products, namely cementitious, dispersion-based, and reaction resin CTAs. This division follows the chemical nature of CTA's binders. The division into three types of CTAs is also related to their application properties and final performance. Of the three types of CTAs, cementitious CTAs account for the dominant market share, and the paper is limited to the study of these three CTAs. Currently, CTAs are produced in modern dry-mix mortar plants, in which individual components (raw materials) are stored in silos. Then, they are weighed and transferred to a high-speed blending mixer, packed, and transported to points of sale or directly to the construction site [11]. Before use, the addition of only water and mixing according to the manufacturer's instructions is required. Since the CTA production process is well defined, automatized, and computer-controlled, the resulting construction product is of a well-defined quality and has specific performance characteristics [11,12].

A breakthrough in the development of cementitious CTAs was the receipt of redispersible polymer powder in the 1950s, which represents significant changes in the economy of Western Europe in the 1970s related to the fuel crisis and a substantial increase in labor costs, and the economic transformation of Central and Eastern European countries in the last years of the 1990s. Although it is debated, the CTA market size was valued in 2018 at USD 15.08 billion [13] or USD 14.38 billion in 2020 [14]. The global CTA market is expected to reach USD 20.17 billion by the end of 2026 [14] and in very optimistic forecasts, which from today's perspective seem unlikely, it is expected to reach 40.73 billion by 2026 [13].

CTAs, although their purpose is always to connect the ceramic tile with the substrate, have different properties depending on many factors. Due to technical criteria, modifying the CTA with a redispersible polymer powder is essential. Redispersible polymer powder is a necessary component of CTAs, which helps them to meet today's expectations and to fulfill higher requirements [11,12,15,16]. In 2020, the redispersible polymer powder market was valued at USD 2.0 billion and projected to grow to 2.8 billion by 2025. The market growth is expected to be primarily driven by the growing economies of the Asia Pacific region (China, India, Japan) [17]. Another criterion that distinguishes CTA is geography, the relationship between the economic level of a given world region, and the technical standards applicable there. It is also visible from the perspective of scientific publications [12,18].

In 2020, the global consumption of ceramic tiles was 16,035 billion square meters. As many as 71.5% of the ceramic tiles were installed in Asia, while in Europe the share was 10.0%, for Central-South America—7.8%, Africa—7.0%, and North America—3.4%. In Europe, 65% of the consumption of ceramic tiles was attributed to European Union countries, which represent 1.035 billion square meters [19]. Assuming the consumption of 4 kg of CTA per square meter of ceramic tile, this means that just over 64 million tons of CTAs was consumed in the world and just over 4 million tons of CTAs was consumed in the EU.

3. Assessment and Verification of the Constancy of the Performance of the CTAs

3.1. European Standard EN 12004

Until 2001, CTA requirements for the AVCP did not exist at the level of all EU countries. This situation made it difficult for the investor and contractor to select the appropriate CTA and made it difficult and often impossible to assess the CTA in comparison to other CTAs objectively. The lack of uniform evaluation criteria resulted in different requirements for the same essential characteristics.

A new era in the standardization of CTAs came after EN 12004:2001 [20] was developed in CEN/TC 67. Following the work of CEN/TC 67, and in principle CEN/TC 67/WG 3, the standard requirements for CTAs presented other editions, i.e., EN 12004:2001+A1:2002/AC:2002, EN 12004:2007, EN 12004:2007+A1:2012 and EN 12004-1:2017. The last standard EN 12004-1:2017 has not yet been published in the list of European harmonized standards [21]. For this reason, the basis for AVCP is EN 12004:2007+A1:2012 [22], which is the last of the versions mentioned above of the standards, specified in the list of harmonized European standards published in the Official Journal of the EU [23]. Although the CPR rules have been in force for the last eight years [1], EN 12004:2007+A1:2012 is a standard from the old legal order, i.e., from the period of Directive 89/106/EEC [24].

The EN 12004 standard, in addition to cementitious adhesives, also applies to dispersion adhesives and reactive resin CTAs. It is worth mentioning that the EN 12004 standard divided cementitious CTAs into the following two main classes: with basic properties, marked as C1, and with enhanced parameters, marked as C2. Table 1 shows the requirements for cementitious CTAs under EN 12004:2007+A1:2012.

Table 1. Requirements for cementitious CTAs according to EN 12004:2007+A1:2012 [22].

Fundamental Characteristics		
Characteristics	**Requirement**	**Test Method**
Normal setting adhesives (C1)		
Initial tensile adhesion strength	≥0.5 N/mm^2	8.2 of EN 1348
Tensile adhesion strength after water immersion	≥0.5 N/mm^2	8.3 of EN 1348
Tensile adhesion strength after heat aging	≥0.5 N/mm^2	8.4 of EN 1348
Tensile adhesion strength after freeze–thaw cycles	≥0.5 N/mm^2	8.5 of EN 1348
Open time: tensile adhesion strength	≥0.5 N/mm^2	EN 1346
Fast setting adhesives (C1F)		
Early tensile adhesion strength	≥0.5 N/mm^2	8.2 of EN 1348
Open time: tensile adhesion strength	≥0.5 N/mm^2	EN 1346
All other requirements as in Table 1a		
Optional characteristics		
Special characteristics		
Slip	≤0.5 mm	EN 1308
Extended open time: tensile adhesion strength	≥0.5 N/mm^2	EN 1346
Deformable adhesive: transverse deformation	≥2.5 mm and <5 mm	EN 12002
Highly deformable adhesive: transverse deformation	≥5 mm	EN 12002
Additional characteristics (C2)		
High initial tensile adhesion strength	≥1.0 N/mm^2	8.2 of EN 1348
High initial adhesion strength after water immersion	≥1.0 N/mm^2	8.3 of EN 1348
High tensile adhesion strength after heat aging	≥1.0 N/mm^2	8.4 of EN 1348
High tensile adhesion strength after freeze–thaw cycles	≥1 N/mm^2	8.5 of EN 1348

It is also important to note that there are requirements for the transverse deformability of CTAs. According to the data presented in Table 1 (special characteristics), it is possible to distinguish two types of cementitious CTAs—S1 (deformable) and S2 (highly deformable).

The last version of EN 12004-1:2017 additionally specified requirements for fast setting cementitious CTAs with increased parameters (C2F). These requirements are presented in Table 2. A separate specification of requirements for fast setting cementitious CTAs, for which requirements were already in the earlier version of the standard (EN

12004:2007 + A1:2012), resulted from the need to clarify misunderstandings in the interpretation of the provisions of the previous version (EN 12004:2007+A1:2012).

Table 2. Requirements for cementitious CTAs according to EN 12004-1:2017 [21].

Optional Characteristics		
Characteristics	**Requirement**	**Test Method**
Fast setting adhesives (C2F)		
Early tensile adhesion strength	$\geq$1.0 N/mm^2	8.3 of EN 12004-2:2017
Open time: tensile adhesion strength	$\geq$1.0 N/mm^2	8.1 of EN 12004-2:2017

All other requirements as in Table 1d of EN 12004-1:2017.

ISO/TC 189 adapted the requirements of EN 12004:2001 and EN 12002:2002 [25], and a series of four ISO 13007 standards specifying requirements and test methods for CTAs and grouts was developed and published in 2004. Since ISO was and still is a global standardization organization, the terminology and technical requirements for CTAs initially published in EN 12004:2001 due to ISO 13007-1:2004 [26] have become commonplace worldwide. ISO last reviewed and confirmed the provisions of the ISO 13007-1:2014 standard in 2019 [27].

3.2. Testing of CTAs

The adoption of tensile adhesion strength and open time (maximum time after CTA application when ceramic tiles can be embedded in the adhesive layer to obtain the tensile adhesion strength value equal to 0.5 N/mm^2 (C1) or 1.0 N/mm^2 (C2)) as the fundamental characteristics of CTAs was criticized [15,28]. It was noted that the shear stresses in the substrate—CTA—ceramic tile system (parallel shear force) would better characterize the system compared to the vertically acting force when determining the tensile adhesion strength. However, the difficulties of shear strength determination are incomparably more significant than the relatively simple task of tensile adhesion strength measurements. For this reason, the shear strength is not normally determined for cementitious tile adhesives.

CTA adhesion measurement is performed after the adhesive has been stored in four different conditions, which simulate the real-life conditions in which the cementitious CTAs are applied. Nevertheless, it is essential to underline that conditioning according to EN 12004 does not always provide information about the long-term service life performance of CTAs. For this reason, there are postulates and proposed methods of assessing the long-term performance of CTAs [29,30]. However, the subject of this review is the assessment of EN 12004. At this stage of the review, it is also important to mention that the determination of the tensile adhesion strength, similar to other measurement methods, is related to the dispersion of the obtained results, which will be discussed in more detail later in this paper [31,32]. Therefore, it is crucial to determine the influence of various factors related to the test method.

An experiment consisting of determining the initial adhesion strength of seven different CTAs in ten laboratories using two other concrete slabs was described by Felixberger [15]. The study organizer provided one of the concretes slabs, and each participating laboratory provided the second. Both concrete slabs were compliant with EN 1323:2007 [33]. As a result of the tests, it was found that the concrete slab affected the value of the determined CTA adhesion. It was also found that for cementitious CTAs characterized by lower tensile adhesion strength values, the differences between individual measurements were more significant than in the case of CTAs with higher adhesion.

The properties of ceramic tiles used for tensile adhesion strength measurements are specified in EN 1348:2007 [34]. Niziurska determined the tensile adhesion strength of CTA using ten different ceramic tiles [35]. All of the tested ceramic tiles met the requirements of EN 1348:2007, and all other materials used in the study were the same. Significant differences in tensile adhesion strength were observed, which did not correlate with the results of the phase composition test, the study of the water absorption of the ceramic tiles, and the observations of the microstructure of the surface of the ceramic tiles. Two years later, in the same laboratory, the influence of the water used for seasoning the samples on the tensile adhesion strength of six different CTAs was tested [36]. Samples of CTAs were stored in three types of water, including distilled water (pH = 7.09, specific conductivity = 0.040 mS/cm), tap water (pH = 8.25, specific conductivity = 0.805 mS /cm) and softened water (pH = 8.63, specific conductivity = 1.228 mS /cm). It was found that the type of water used for seasoning samples has a great influence on the adhesion of CTAs (differences between the average tensile adhesion strength values ranging from 16% to 66% in the case of one of the CTAs were observed). Samples stored in distilled water were characterized by higher adhesion than those stored in tap water or softened tap water.

3.3. Interlaboratory Tests of CTAs

From the perspective of the manufacturer responsible for the construction product placed on the market, it is crucial to reproduce the results, i.e., test results of the same product obtained using the same method in different laboratories by different operators using other equipment. Each laboratory needs to confirm its competence independently, which enables their participation in proficiency testing (PT). It is one of the three types of interlaboratory comparisons (ILCs) in which a much larger population of commercial (manufacturer) laboratories can take part. The primary purpose of PT is to check the homogeneity of the pool of results obtained for a specific product and determine what part of the results fall [37]. Requirements for the competencies of the organizers and the development and implementation of PT are set out in EN ISO/IEC 17043:2010 [38].

In 2007, the Romanian laboratory Ceprocim (notified laboratory in the scope of EN 12004) started PT of CTAs. Nine laboratories, most of them Romanian, participated in the first edition of the project in 2008–2009 [39]. Twenty-seven laboratories from nine countries (Austria, Bulgaria, Croatia, the Czech Republic, Germany, Poland, Portugal, Romania, and Slovenia) participated in the fifth edition [40]. Twenty-seven laboratories from Austria, Germany, Greece, Italy, Mauritius, Poland, Portugal, Republic of Moldova, Romania, Slovenia, Spain and the United Arab Emirates participated in the last edition, the twelfth, of PT [41]. Participants of all editions of PT represented both accredited and non-credited laboratories according to EN ISO/IEC 17025 [42]. The *z*-score analysis showed that more than 90% of the test results obtained by participating laboratories could be described as "satisfactory" according to EN ISO/IEC 17043. The remaining effects were questionable or unsatisfactory in some editions [39–41]. Twelve editions of the PTs unambiguously demonstrated that constant participation in laboratory PT programs improves the quality of the work of laboratories. In this respect, the organizers of the study achieved the intended goal [39–41]. However, this evaluation was performed from the perspective of the requirements of EN ISO/IEC 17043, i.e., a standard which specifies general requirements for the development and implementation of PT. These requirements are intended for application to all PT programs for different technical requirements in other application areas. Additionally, in this respect, PTs [37,43] are primarily assessed. For PT measurements organized by Ceprocim, among the laboratories classified as "satisfactory", some provided 1.3 N/mm^2 and some obtained the result of 2.4 N/mm^2. From the producer's perspective, these are significant differences. Such significant differences can mean that the product is non-compliant with requirements in many cases. The results of PTs are not satisfactory from the perspective of manufacturers of CTA. Manufacturers of CTAs, who are aware of the "imperfections" of the tensile adhesion strength measurement, have to consider it in their risk analysis. Otherwise, it CTAs may not meet the acceptance criteria in re-assessments of the product conducted by market surveillance authorities [44,45]. Additionally, market surveillance authorities in Poland apply the simple acceptance rule when assessing a construction product, which does not consider the variability resulting from measurement uncertainty [45].

4. Conclusions

The EN 12004 standard was a crucial element in organizing the EU CTAs market. Following the adoption by ISO of the classification and test methods specified in EN 12004, the requirements for CTAs were harmonized worldwide.

The research on the influence of auxiliary materials (concrete slabs and ceramic tiles) used in the tensile adhesion strength measurement showed that they significantly impact the result. In some cases, they may determine whether or not the obtained value meets the acceptance criteria. This situation is unsafe for the manufacturer when the actual properties of the CTA do not differ much from the threshold value, which is the basis for the product evaluation. Each producer that places a product on the market is exposed to the risk that the product assessed by market surveillance authorities will not be positively verified. For this reason, it is essential to be aware of the uncertainty value in the study of a given characteristic. Considering the variability resulting from measurement uncertainty in the risk analysis, the manufacturer can minimize the risk of a negative assessment by market surveillance authorities.

The results of the multi-annual ILCs/PTs of CTAs have shown that, on the one hand, laboratories participating in the PTs obtain primarily satisfactory results. Undoubtedly, continuous participation in PTs increases laboratory competence. On the other hand, acceptable differences from the perspective of the testing laboratory may or not even be sufficient for producers.

In the light of the test results described above, it is reasonable to consider an amendment to the requirements of EN 12004 and an obligatory consideration of the measurement uncertainty in the assessment of CTAs. Differences between test results obtained in different laboratories are a natural phenomenon, and the value of measurement uncertainty indicates the range of differences. However, assessments and verification of the constancy of performance should consider the measurement uncertainty in this assessment due to the specificity and imperfections related to tensile adhesion strength measurements. The new EN 12004 should also consider a procedure for doubtful cases.

As previously mentioned in the assumptions, standardization works use proven achievements of science and technology, are carried out in openness, take into account the public interest, which is very important and participation is voluntary. The consensus is the basis of the standardization process. The final product of this work, which is a standard, is perceived differently by the standardization bodies themselves, authorities, primarily market surveillance, science, customers, and industry. The situation in testing the adhesion of ceramic tiles adhesives described in this review perfectly illustrates how difficult it is to create a standard that satisfies all stakeholders.

To illustrate the complexity of the situation described in the review in the scope of measuring the adhesion of CTAs according to EN 12004, Figure 1 presents in a new approach the test results described in the recently published results of the study comparing two editions of ILCs [46]. The bottom part of Figure 1 shows the tensile adhesion strength results of the same CTA, a class C2 adhesive, determined after immersion in water, which was obtained by nineteen testing laboratories participating in the study and distinguishing the dominant failure pattern (two different colors). Ten laboratories indicated cohesive failure pattern (CF-A) as dominant, and seven as the dominant failure pattern indicated adhesive failure between the adhesive and tile (AF-T). Two out of nineteen laboratories showed a mixed failure mode model, i.e., 5% CF-A and 95% AF-T in one case and 20% CF-A and 80% AF-T in the second one. The middle part of Figure 1 shows the results of the z-score analysis, which is used to determine the competencies of laboratories participating in the ILCs. In the case of eighteen laboratories, z-scores were obtained and classified according to ISO 13528 [47] as "satisfactory", i.e., meeting the condition $|z| < 2$, marked in green in Figure 1. Only in the case of one laboratory (marked as number 15) was the value of the z-score above 2.0, which, following the requirements of ISO 13528, means that the obtained result was classified as "questionable". In the upper part of Figure 1, the result of the construction supervision authority assessment is presented using a simple acceptance rule that does not consider the variability resulting from the measurement uncertainty.

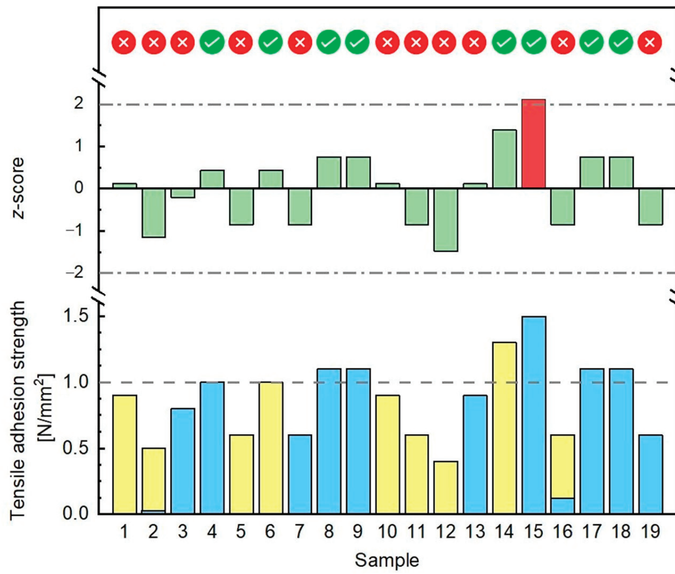

Figure 1. The results of the tensile adhesion strength of class C2 cementitious tile adhesive (CTA) after immersion in water obtained by nineteen laboratories participating in the ILC [46]. Legend: (■) adhesive failure between adhesive and tile (AF-T); (■) cohesive failure within adhesive (CF-A); (■) $|z| < 2$ (satisfactory); (■) $2 < |z| < 3$ (questionable); (✓) samples that were assessed by the construction supervision as meeting the requirements for CTA class C2 (>1.0 N/mm^2 following EN 12004); (✕) samples that the construction supervision assessed as not meeting the requirements for CTA class C2.

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standards

Review

Eurachem/CITAC Guide "Assessment of Performance and Uncertainty in Qualitative Chemical Analysis"—A Medical Laboratory Perspective

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Abstract: *Background*: The performance assessment of tests that express qualitative results in the medical laboratory is of primary importance in characterization, diagnosis, follow-up, and screening. An important contribution to this type of assessment may be the publication of the Eurachem AQA 2021 guide. The text intends to principally discuss the consistency of the subclauses of this guide with ISO 15189 and CLSI EP12-A2. *Methods*: The study involves a literature review within the scope of qualitative tests. *Results*: Tables are used for crossing AQA. with ISO 15189 and CLSI EP12-A2. *Conclusions*: Consistency with ISO 15189 and CLSI EP12-A2 is demonstrated in the study. Introducing "uncertainty of proportion" reflects the necessity of assessing uncertainties when dealing with qualitative results.

Keywords: clinical; CLSI EP12; ISO 15189; qualitative; sensitivity; specificity

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1. Introduction

1.1. The Performance Assessment of Qualitative Results in the Medical Laboratory

The quality control principles in the medical laboratory became more systematized from the 1970s onward. This was due to a vast number of publications that transposed and reviewed approaches to chemistry from a clinical perspective. This development mainly focused on tests that express quantitative quantities, such as 20 IU/L of alanine aminotransferase (ALT). The methodologies initially focused on validation and later on internal quality control (IQC) and external quality assessment (EQA). The availability of guides for evaluating the performance of quantitative tests is vast, with the majority, within the medical laboratory, published by the Clinical Laboratory Standards Institute (CLSI) [1], a global agency. CLSI is an international not-for-profit group that develops laboratory standards for use in the medical laboratory stakeholders using volunteers' expertise. Its standards are recognized by medical laboratories, accreditors, government agencies, and manufacturers of *in vitro* diagnostic medical devices (IVDDs) as reference techniques for improving medical laboratory testing.

Aside from measurement uncertainty [2], we can argue that the medical laboratory's specific performance assessment methods comply with the general principles embodied in the relevant standards, such as ISO 15189 [3]. Medical laboratories can use this global standard to develop quality management systems and assess their own competence by accrediting laboratory tests and methods [4]. As a result of current performance assessment methodologies, laboratories can prove that they operate effectively, even complying with ISO/IEC 17025 [5]. Similar considerations can be made of the various national legal regimes and the manner in which IVDDs are regulated. [6,7].

We emphasize the role of the International Organization for Standardization (ISO), which has developed over 24,222 international standards. A total of 167 national standard-setting bodies are members of ISO, an independent, non-governmental international organization. We can confidently say that no other global organization has contributed as much to harmonizing practices in industry and services, with ISO 15189 being one of the examples in the medical laboratory.

When it comes to tests that express qualitative results, the number of publications is much smaller. For example, compared to quantitative assessments, CLSI has published a small number of documents for qualitative performance assessment, with the central guide being EP12-A2 [8], which is under review. The evaluation methodology in this type of study focuses on Bayesian probability [9], often crossing with epidemiological principles. Concepts such as uncertainty are not usually associated with these assessments. Performance is generally assessed through clinical sensitivity and clinical specificity, which are the proportions of true results for a given condition (5.3 of [8]), e.g., SARS-CoV-2-infected individuals (condition), and the proportion of negative results in the absence of a given condition (clinical specificity), i.e., in healthy individuals. Both are immediately identified as estimates of diagnostic accuracy. Even when the 95% confidence interval (CI) for these proportions is calculated, the evaluation usually focuses solely on the absolute clinical sensitivity and clinical specificity values. A review of this guide can be found anywhere [10].

The COVID-19 pandemic highlighted the importance of diagnostic accuracy assessment in screening tests. The evaluation, like the one exposed by the Foundation for Innovative New Diagnostics (FIND), a global health nonprofit organization based in Geneva, Switzerland, and a World Health Organization (WHO) Collaborating Center for Laboratory Strengthening and Diagnostic Technology Evaluation, allowed us to assess which test is recommended for screening, in addition to differentiating the performance of both real-time polymerase chain reaction (RT-PCR) tests for ribonucleic acid (RNA) detection and tests for anti-IgG/IgM antibodies of SARS-CoV-2 [11].

1.2. Eurachem and CITAC

Eurachem is a European network of organizations to establish a system for the international traceability of chemical measurements and promote good quality practices. The organization provides a forum for discussing common problems and developing an informed and considered approach to technical and policy issues. Eurachem promotes best practices in analytical measurement by producing authoritative guidance within its expert working groups, publishing guides on the Web, and supporting workshops to communicate good practice. The guidance covers technical issues such as measurement uncertainty evaluation, method validation, and EQA [12].

The Cooperation on International Traceability in Analytical Chemistry, abbreviated to CITAC, is a global organization that aims to discuss how analytical activities could be developed to meet the needs, and it has identified a wide variety of issues to be addressed to ensure that analytical measurements made in different countries or at different times are comparable. These range from developing traceable reference materials and methods to harmonizing analytical quality practices [13].

1.3. Eurachem Qualitative Analysis Working Group

At the Eurachem/CITAC workshop in Lucerne in June 2002, a workshop session was held on qualitative analysis and testing uncertainty. That workshop recommended forming a new Eurachem working group to guide the topic; on the basis of the discussion paper presented at that meeting, the Qualitative Analysis Working Group (QAWG) was created. It aims to prepare guidance on the assessment and expression of uncertainty in qualitative analysis and testing and arrange for appropriate publication and promotion of the above guidelines.

The QAWG was responsible for authoring the first edition of the guide "Assessment of performance and uncertainty in qualitative chemical analysis AQA 2021". The approval date comprised 15 participants from Eurachem member organizations and two participants from CITAC members. The guide is a milestone in Eurachem/CITAC publications, as it is the first on qualitative tests in chemistry.

1.4. Eurachem/CITAC Guide "Assessment of Performance and Uncertainty in Qualitative Chemical Analysis"

Qualitative analysis is frequently used in several analytical fields, such as medical laboratories, where this guide draws upon the experiences of these fields. The manual is intended to assist laboratory staff in choosing and implementing methods to assess the quality of qualitative chemical analysis methods and evaluate uncertainties associated with qualitative chemical analysis. Its purpose is to establish the quantitative reliability of a qualitative analysis result.

The Eurachem/CITAC guide takes into account the following types of criteria:

(a) "Quantitative criteria in which a numerical result is used to categorize a test item as belonging to a pre-established class";
(b) "Qualitative criteria such as the presence or absence of a particular feature, color change on a test, etc." (2 of [14]).

However, it is not centered on binary ordinal quantities, such as those with 0/1 or yes/no values that can be ordered by size, such as positive/negative results classified on an ordinal scale according to a clinical decision point/cutoff. It deals mainly with nominal properties, i.e., with values without size, such as agglutination/no agglutination [15].

The guide, after the introduction, presents the types of qualitative analyses. The performance assessment for qualitative analysis is discussed, involving expressions of confidence in qualitative analysis. Afterward, it suggests how to report the qualitative analytical result. Lastly, conclusions and recommendations emerge, as well as six examples, including the performance assessment in detecting SARS-CoV-2 RNA by nucleic acid amplification.

1.5. Rationale and Objectives

The review of this guide is necessary for the medical laboratory, as it is a guide issued by organizations with peer-reviewed solid publications, as evidenced by the vast number of citations. Although the guide is not exclusive to the medical laboratory, it is covered through keywords with ISO 15189, clinical sensitivity, clinical specificity, and uncertainty of proportions. The guide even features a performance assessment example for an RT-PCR test. In other words, part of the target audience of this document is the medical laboratory staff.

The purpose of this review is to answer the following questions:

(a) How important is the guide to performance assessment of qualitative tests in the medical laboratory?
(b) Can the guide's approach satisfy the technical requirements regarding performance assessment?
(c) Does it fit ISO 15189 requirements?
(d) Does it fit CLSI EP12-A2 recommendations?

2. Materials and Methods

The survey was carried out at PUBMED [16], in December 2021, with the following keywords: analysis, assessment, chemical, Eurachem, performance, qualitative, and uncertainty. The data collection process involved two independent reviewers. No review was found for AQA 2021 publication; therefore, this review did not consider eligibility criteria and study selection. Published reviews would not be expected regarding the publication date of the AQA 2021 (17 November 2021) and the writing date of this text (December 2021). Therefore, the risk of a biased study appears to be negligible.

The sources used were the Eurachem website, specifically its pages "About Eurachem", "Eurachem guides", and "Assessment of performance and uncertainty in qualitative chemical analysis". On the CITAC website, we only consulted the "About CITAC" page. The AQA 2021 is freely accessible. ISO 15189 and CLSI EP12-A2 were already part of our portfolio of documents, which are paid for. The "Guidance on performance evaluation of SARS-CoV-2 *in vitro* diagnostic medical devices" by the Medical Device Coordination Group Document of the European Commission is openly accessible on its page [17]. We also consulted the "Medical Devices Sector" websites of this Commission [6] and that of the US Food and Drug Administration (FDA) "Medical Devices" [7].

3. Results

In the tables, crossings between clauses or subclauses are noted with a cross. We can understand that the crossed clauses or subclauses comprise similar and replicable methodologies in medical laboratory practice. The clauses or subclauses were identified on the basis of their fit for the purpose of the AQA 2021 in the medical laboratory. Crossing with related clauses or subclauses in whole or in part was allowed.

In the ISO standard, only subclauses related to intra-laboratory performance assessment were considered to have the comparison within the same scope. For example, subclauses 5.6.3 "interlaboratory comparisons" and 5.6.4 "comparability of examination results" are somehow out of focus in this study, so they are not discussed.

Considering the application of the AQA 2021 guide in the medical laboratory, we consider it to crosse with the technical requirements of ISO 15189. Table 1 shows this crossing. The AQA 2021 and CLSI EP12-A2 technical guides were a second cross. Table 2 presents this crossover.

Table 1. AQA 2021 vs. ISO 15189 clauses.

	AQA 2021								
ISO 15189	**2 Types of Qualitative Analysis**	**3.2 Quantification of Qualitative Analysis Performance**	**3.3 Evaluating False Positive and False Negative Rates**	**3.4 Limit of Detection and Selectivity**	**4.2 Likelihood Ratio**	**4.3 Posterior Probability**	**4.4 Reliability of Metrics**	**4.5 Uncertainty of Proportions**	**5 Reporting the Qualitative Analytical Result**
5.5.1.2 Verification of examination procedures	X	X	X	X	X	X	X	X	X
5.5.1.3 Validation of examination procedures	X	X	X	X	X	X	X	X	X
5.5.1.4 Measurement uncertainty of measured quantity values								X [1]	

[1] Measurement uncertainty is not an ISO 15189 requirement for tests that do not express a quantitative value.

Table 2. AQA 2021 vs. CLSI EP12-A2 clauses.

	AQA 2021								
CLSI EP12-A2	**2 Types of Qualitative Analysis**	**3.2 Quantification of Qualitative Analysis Performance**	**3.3 Evaluating False Positive and False Negative Rates**	**3.4 Limit of Detection and Selectivity**	**4.2 Likelihood Ratio**	**4.3 Posterior Probability**	**4.4 Reliability of Metrics**	**4.5 Uncertainty of Proportions**	**5 Reporting the Qualitative Analytical Result**
6 Device familiarization and training		X							
7 Evaluation materials		X	X	X	X			X	
8 Bias and imprecision studies									
9 Comparison methods		X	X		X	X	X	X	
10 Data analysis		X	X		X	X	X	X	X
6 Device familiarization and training		X							

4. Discussion

Table 1 shows a significant crossover between AQA 2021 and ISO 15189. "Verification", in the ISO standard, comprises the performance assessment of validated examination procedures used without modification before being introduced into routine use. It refers to commercialized tests that have already exhausted validation by the manufacturers of *in vitro* diagnostic medical devices and are approved by a notified body, as is the case in the European Union or the US. On the other hand, the "validation" of examination procedures is derived from the following sources: (a) nonstandard methods; (b) laboratory designed or developed methods; (c) standard methods used outside their intended scope; (d) validated methods subsequently modified. Compared to verification, validation involves more complex models, for example, determining the cutoff in an "in-house" test. The verification fundamentally aims to know if the manufacturer's performance is replicable in the laboratory. The deferent clauses can be operationalized through the AQA.

The crossing with CLSI EP12-A2 clauses is shown in Table 2. We can understand that both the CLSI guide and the AQA 2021 aim to operationalize the technical requirements stipulated mainly in subclauses ISO 15189 5.5.1.2 and 5.5.1.3. The mathematical models for determining clinical/diagnostic accuracy, i.e., clinical sensitivity and clinical specificity, are the same as those of the CLSI EP12-A2. As expected, they are based on Bayesian probability [9]. The same is true for other probabilities computed from a 2 × 2 contingency table, such as positive and negative predictive values. While clinical accuracy is more relevant to the performance assessment of a given qualitative test, predictive values are more important to the physician. While the former is the proportions of true results in samples with a particular condition and without that condition, as mentioned above, the predictive values are the proportion of individual results with a specific condition and without that condition in positive and negative samples, respectively.

Whenever the diagnosis is unknown, it is possible to calculate, alternatively, the agreement of positive and negative results. Similarly to diagnostic accuracy, both are calculated from the results of the contingency table. Mathematical models are similar to sensitivity and specificity. In this case, the ratios are influenced by non-concordant results.

Compliance assessment is one of the most important and least harmonized topics, not being clear to all medical laboratories when validating clinical sensitivity and specificity results. The European Commission has published some guides on the performance evaluation of *in vitro* diagnostic medical devices, such as SARS-CoV-2 [18]. This document includes specimen type, number of samples, and acceptance criteria for the different performance assessment parameters. As a rule of thumb, the medical laboratory must set clinical sensitivity and specificity targets depending on the intended use of its results. Let us consider the blood bank case versus the clinical pathology laboratory. The sensitivity/specificity tradeoff in blood banks favors sensitivity to minimize the risk of false-negative results, implying a high risk of post-transfusion infection. In contrast, in a pathology laboratory, the sensitivity may be lower than 100% because we can retest a patient without causing harm to third parties. Compliance assessment is poorly discussed in AQA 2021 and EP12-A2. Eurachem

The most significant difference in the diagnostic accuracy approaches is probably due to the view introduced by the AQA, which is based on publications by Pereira et al. [19] (4.4.6 of [20]): uncertainty of proportions. The calculation model is the same as published in the CLSI guide EP12-A2 for 95% CI for clinical sensitivity and clinical specificity. A 95% score confidence interval, attributed to Wilson [21], is calculated in both guides. The two-sided 95% CI for sensitivity or specificity must exceed the lower bound criteria. The criteria are easy to compute; a fixed n is considered for each sample type, or the requirements are recalculated according to the n. For example, for $n = 10$ infected samples, the lower bound criterion is 72%, which happens when sensitivity is 100%. On the other hand, if specificity of 95% is acceptable, the lower bound criterion is 88.8%.

The introduction of the term "uncertainty of proportions" can be understood as a milestone; as far as we know, it is the first global guide to address the uncertainty of binary positive/negative data. This model is easily replicable for other qualitative outcomes such as blood groups and karyotypes. In fact, the concept is similar to the expanded measurement uncertainty, which is also associated with a 95% CI. Thus, a larger interval expressing the uncertainty indicates a lower likelihood of the sensitivity or specificity value being in the population with the epidemiological characteristics of the samples studied, with a 95% confidence and a beta and alpha risk of 5%. We believe that this introduction will demystify the principle of "impossibility of calculation" in qualitative expressions. This myth is most likely because the measurement uncertainty is solely for quantitative expressions. Note that, for example, subchapter ISO 15189 5.5.1.4. does not apply to qualitative test results.

For a clearer understanding of the uncertainty of proportions, let us present an example test for screening for antibodies against the hepatitis C virus (HCV) by immunoassay. The performance assessment study involves 20 samples from patients diagnosed with HCV infection and 80 healthy subjects. The claimed clinical sensitivity and specificity results are 100% and 90%, respectively. For the target uncertainty in these proportions for a 95% CI, lower bound criteria of 84% for sensitivity and 82% for specificity are claimed. We can interpret that false-negative results are not allowable, admitting up to eight false-positive results. Absolute values are 100% and 99% for sensitivity and specificity, respectively. Therefore, the test is valid according to the first criterion. The lower limits of the 95% CI were 84% for sensitivity and 93% for specificity; hence, the probability of true results is lower than what was claimed. Note the importance of the consistency of claimed results with the number of false results allowed and the number of samples tested.

CLSI EP12-A2 presents a qualitative method-precision experiment for measurand concentrations near the cutoff (C_{50}) (8.3 of [8]), recognized as the "C_5-C_{95} interval", which, as we can understand, is harmonized with IVDD manufacturers. This model is rarely used in the medical laboratory. Anyway, it could be important for "in-house" or modified tests since it lets you know the consistency of "high negatives" and "low positives" in true results with 95% confidence (95% trueness). Low positives should report 95% of positive results. This template is not part of the AQA content.

The area under the receiver operating characteristic (ROC) curve (AUC) [22] fundamentally determines the cutoff point in tests during development, based on the clinical sensitivity/specificity tradeoff. This model allows, for hypothetical cutoff values, to know the clinical sensitivity and specificity for each point. The "best" cutoff is chosen according to the intended use of the reported results. In fact, the cutoff is selected on the basis of the performance assessment of each candidate point. For example, in a blood bank, sensitivity is favored over specificity. None of the guides provides a sufficient discussion of their use in the medical laboratory.

Even though measurement uncertainty can be important in calculating the "gray zone" [23] in ordinal qualitative tests, binary results are classified by comparing a numerical result as a function of a clinical decision point (cutoff). Depending on the order relative to the cutoff, it is classified as positive or negative. For example, if we use the signal-to-cutoff ratio (S/CO), where the cutoff is one, positive is equal to or higher than one, and negative is lower. Pereira et al. [24] demonstrated the calculation of measurement uncertainty in ratios close to this decision point. From this uncertainty, the "guard band"/"gray zone" was calculated, in which the results were classified as indeterminate. The importance of a ternary classification depends on the fitness for the purpose/intended use of the reported results. Again, it will be more significant in a blood bank than in a clinical pathology laboratory. The empirical determination of the "gray zone" is not referred to in any of the guides. Previously, Dimech et al. [25] published a measurement uncertainty study of screening immunoassays based on EQA data.

Furthermore, another important performance assessment tool in this type of test is the detection limit. This limit is measured in molecular biology tests, such as RT-PCR. This value is also recognized as "analytical sensitivity", i.e., the value from which we have 95% true positives, identified as a "95% hit rate", e.g., 10^2 target RNA copies per reaction. Its determination employs probit regression (5.5 of [26]), also called the probit model. It is used to model dichotomous or binary outcome variables. The inverse standard normal distribution of the probability is modeled as a linear combination of the predictors. It is closely related to the logit function and logit model. This model is not covered in EP12-A2. Despite being referred to in the AQA, it is not presented in detail.

Lastly, let us discuss the importance of the delta value in test performance (4.5 of [20,27]). This tool is important when at least two tests have identical performance assessments, e.g., when clinical sensitivity is equal. The delta value answers the following question: "Which of these tests is most likely to report false or indeterminate results?". This question is important, mainly in validating blood components in blood banks or human organs, cells, and tissues. What is intended to be mitigated goes beyond the risk of false results. It also includes the risk of a negative impact on budget and stock. For example, it is recognized in the case of false results as it implies retesting, elimination of blood components, and suspension of blood donors. Delta values are determined separately for individuals with positive and negative conditions, abbreviated as $\delta+$ and $\delta-$, respectively. The results are interpreted as follows: a higher delta value indicates a lower tendency for a test to produce false or indeterminate results in human samples with the same epidemiological prevalence as the study samples. This approach is not covered in any of the guides.

5. Conclusions

The Eurachem/CITAC technical guide "Assessment of performance and uncertainty in qualitative chemical analysis" is suggested to operationalize the ISO subclauses to verify and validate examination procedures. At this point, AQA 2021, open-source, is an alternative to EP12-A2, being consistent with its methodologies. The AQA examples of clinical sensitivity and specificity are easily replicable in the medical laboratory. It would be important for the compliance assessment to be discussed in depth in future reviews of both guides. The introduction of the uncertainty of proportions allows the medical laboratory to assess the uncertainty in this type of test, which is a surplus concerning ISO 15189. Compared to EP12-A2, no limitations emerged when applying the AQA in the medical laboratory. However, both guides have limitations, especially in validation or even developmental studies. They do not include complimentary performance assessment models, such as the cutoff determination, even though the EP12-A2 allows us to assess their consistency with the "C_5-C_{95}" principle. Another missing point is the computation of the "gray zone", which is important in human product banks for transfusion or transplantation, and the delta value.

Considering the similarities with EP12-A2, it is likely that AQA 2021 could serve as another essential guide for medical laboratory stakeholders, such as med labs, regulatory agencies and IVDD manufacturers.

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Flood–Ebb and Discharge Variations in Observed Salinity and Suspended Sediment in a Mesotidal Estuary

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Abstract: To explore the spatial and temporal variations in salinity and suspended-sediment concentration in the Danshuei River estuary of northern Taiwan, two intensive field surveys were conducted in July 2016 and 2019 to assign high- and low-flow conditions, respectively. According to the analysis of tidal characteristics, the duration during ebb tide was longer than that during flood tide, while the maximum ebb discharge was higher than the maximum flood discharge, causing the occurrence of tidal asymmetry during ebb and flood tides. The barotropic forcing dominated during high flow, resulting in lower salinity and a shorter distance of saltwater intrusion. Based on the analyzed results using stratification indices, most of the time was spent in the state of partial mixing at the Guandu Bridge and good mixing at the Taipei Bridge during high flow, while most of the time was spent in the states of partial mixing and good mixing at both Guandu Bridge and Taipei Bridge during low flow. More stratification occurred during high flow at high slack tide compared to that during low flow. The freshwater discharges from upriver reaches controlled the suspended-sediment concentration (SSC) in tidal estuaries. The higher SSC appeared downstream of the tidal estuary at ebb tide during high flow. Observations also revealed that there was an estuarine turbidity maximum at the bottom layer of Guandu Bridge.

Keywords: flood–ebb; freshwater discharge; salinity; suspended sediment; mesotidal estuary; environmental monitoring

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1. Introduction

Estuaries and tidal rivers are often densely populated and well-developed commercial areas because of their abundant water, convenient shipping, and high water-use value. Many famous ports such as Shanghai, Baltimore, and Hamburg, and national capitals such as Washington, London, and Taipei are all located in estuaries or tidal rivers. In the second half of the last century, due to the development of industry and commerce, the large population concentration, and the high utilization of rivers by humans, the water bodies of many estuaries and tidal rivers have become overloaded. Not only have the aquatic environment and water resources been destroyed, but they can even cause serious pollution. Poor water quality seriously affects human health and urban landscapes and even results in ecosystem destruction [1–4].

Tidal rivers are transitional waters where rivers flow into the ocean. This transitional water system connects rivers and oceans with two different characteristics. In the tidal reach, the dynamic factors of the ocean and the river both exist and act at the same time, forming a special process of riverbed evolution. The salt-intrusion section in the lower reaches of the tidal river is called the estuary. Generally, among the various dynamic factors in the estuary area, the main effect is dominated by the freshwater discharge and the tide of the river. In each section of the tidal river, the magnitude of the main effect caused is different because of changes in topography, landform, and river course. Therefore, estuaries are all intertwined with the characteristics of physics, biogeochemistry, and ecology [5–9].

The hydrodynamic conditions of estuaries and tidal rivers possess the characteristics of inland rivers, in which freshwater discharge is subject to seasonal variations during flood and dry periods, and oceanic characteristics, such as the rise and fall of tides and variations in spring and neap tides, and the impact of wind shear on velocity fields. In the estuarine area, due to the interaction of freshwater and seawater, there are other issues, such as estuarine circulation, salt and freshwater mixing, and saltwater intrusion, which are far more complicated than streams and rivers. Therefore, to understand the water quality of estuaries and tidal rivers, understanding the hydrodynamics in estuaries and tidal rivers, including freshwater discharge, tidal fluctuations, saltwater intrusion, and salt and freshwater mixing, is a necessary first step [10–18].

In addition to salt intrusion in tidal estuaries, sediment transport is also an important physical phenomenon. Dynamic estuarine processes dominate the distribution and transport of suspended sediment. Understanding suspended-sediment transport is of crucial importance for monitoring water quality and predicting the impacts of suspended sediment on marine ecosystems, particularly the occurrence of estuarine turbidity maxima (ETM) in tidal estuaries [19–25].

Researchers have developed several different kinds of models to investigate the hydrodynamics, salt intrusion, and suspended sediment in tidal estuaries [26–31]. Before the development and application of numerical models, field observations to collect model-validation data are essential [32–34]. Hsu et al. [35] conducted monthly field surveys in the Danshuei River estuary in 2003. They found that the water column (i.e., salinity) was well mixing at the slack before ebb (SBE) and highly stratified at the slack before flood (SBF) at the river mouth. The water column was highly stratified both at the SBE and SBF at the Guandu Bridge. A local turbidity maximum in the bottom water at the Guandu Bridge occurred resulting from deep depression of the bathymetric feature.

Based on field measurements to collect in situ datasets during low- and high-flow conditions, the main objective of this study was to investigate the variations in salinity and suspended-sediment concentration that are subjected to the effects of flood–ebb and freshwater discharge in the Danshuei River estuary of northern Taiwan and to reinforce the possibility of applying hydrodynamic and sediment transport models.

2. Materials and Methods

2.1. Description of Study Area

The study area is located in the Danshuei River estuary, which is the largest tidal river in northern Taiwan and consists of three major tributaries, including the Dahan River, Xindian River, and Keelung River (see Figure 1). The watershed area of the Danshuei River is 2728 km^2, and the total river length is approximately 327.6 km. The mean river discharges of the Dahan River, Xindian River, and Keelung River are 38.99 m^3/s, 69.73 m^3/s, and 25.02 m^3/s, respectively. A Q_{75} flow equal to or exceeding 75% of time is defined as the low-flow condition. The Q_{75} river discharges at the three tributaries are 3.74 m^3/s, 11.6 m^3/s, and 3.5 m^3/s, respectively [36].

The tidal power of the Danshuei River originates from the open sea, and the tidal wave propagates upstream from the river mouth. The tidal elevation is mainly dominated by semidiurnal tides (M_2 and S_2), the mean tidal range is approximately 2.22 m, and the spring tidal range reaches 3.1 m [37].

The salinity distribution of the Danshui River is mainly affected by tidal variations, and the limit of salt intrusion of each tributary is quite different during the slack before ebb and the slack before flood. In addition, the salinity distribution is also controlled by the river discharge and moves upstream and downstream accordingly [38]. Suspended particles in water bodies are affected by tides and salinity. The position of the turbidity maximum in suspended sediments is often located at the Guandu Bridge and upstream reaches, which are approximately 20 km away from the river mouth in the Dahan River and approximately 23 km away from the river mouth in the Keelung River. In the upstream reaches, the cause of the turbidity maximum would be closely related to the limit of salt intrusion, where the residual current is close to zero, allowing the suspended sediment to settle more easily. The other reason would be a high concentration of suspended sediment carried by the upstream reaches. The deep riverbed and the strong residual circulation that occurred at Guandu Bridge resulted in a turbidity maximum [35].

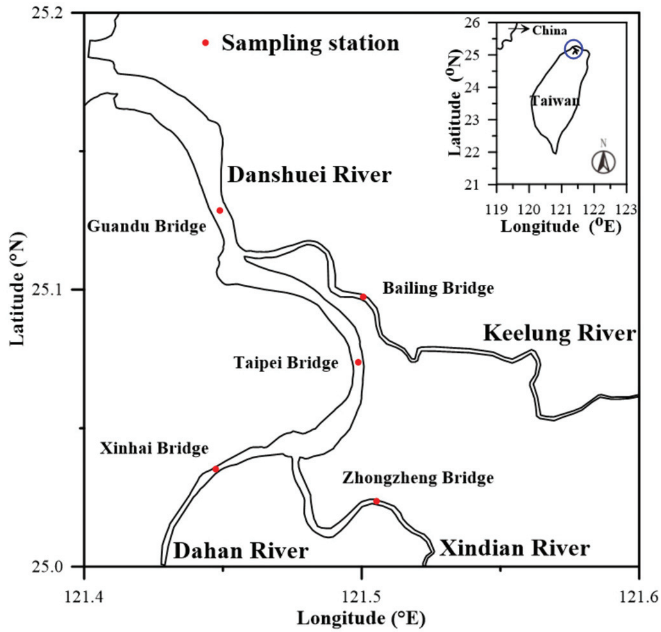


Figure 1. Map of the tidal Danshuei River system and sampling stations.

2.2. Field Survey and Data Collection

Two intensive field measurements at five transects were taken on 4 July 2016, and 17 July 2019, to represent high-flow and low-flow periods. The freshwater discharges from the upstream reaches of the Dahan River, Keelung River, and Xindian River were 23.75 m^3/s, 6.48 m^3/s, and 135.91 m^3/s, respectively, during high flow and 4.3 m^3/s, 3.28 m^3/s, and 19.6 m^3/s, respectively, during low flow. Because the total river discharge (i.e., 166.14 m^3/s) from the tributaries on July 4, 2016 was higher than the total river discharge with mean river discharge (i.e., 133.74 m^3/s), the river discharges on 4 July 2016 were recognized as the high-flow condition. The total river discharge (i.e., 28.17 m^3/s) on 17 July 2019 was similar to the Q_{75} low-flow condition, therefore this date was regarded as the low-flow period. The measured stations covered the Guandu Bridge, Taipei Bridge, and Xinhai Bridge in the Danshuei River/Dahan River, the Bailling Bridge in the Keelung River, and the Zhongzheng Bridge in the Xindian River. The survey periods of two intensive field measurements were from 4 am to 8 pm and the measurement was conducted every hour.

The water samples for total suspended-solid (TSS) concentration and salinity were collected in the field and measured in the laboratory. The sample for TSS was mixed by shaking and then filtered using a weighted standard glass-fiber (0.7 μm pore size) filter. The residue retained on the filter was dried to constant weight at 103 °C to 105 °C. The increase in weight of the filter was assumed to represent the TSS [39]. The vertical salinity was measured with a conductivity–temperature–depth (CTD) sensor for each intensive survey. During each survey, a 600 Hz acoustic Doppler current profiler (ADCP) (RD Instrument, Inc. Poway, CA, USA) was used to measure velocity. The RiverSurveyor Live software was used for data repossessing of ADCP. Figure 2 illustrates the instrumentation photographs used in the field survey.

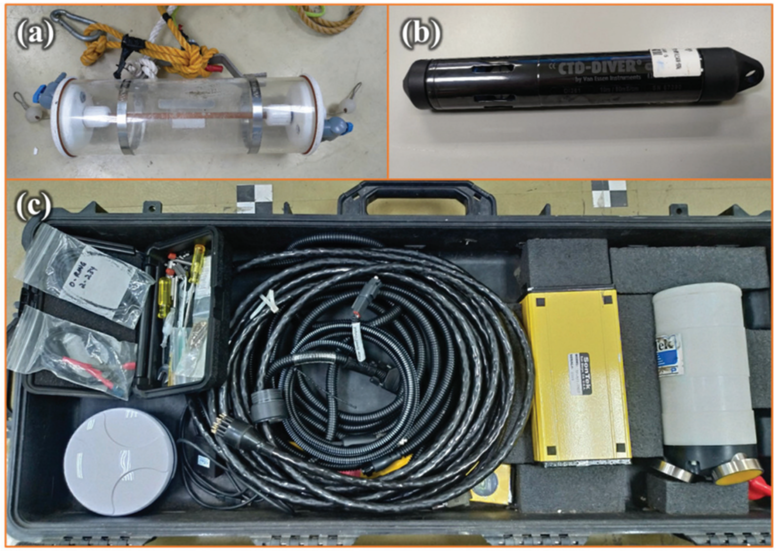


Figure 2. Instrumentation photographs (**a**) water collector, (**b**) conductivity–temperature–depth (CTD) sensor, and (**c**) acoustic Doppler current profiler (ADCP).

2.3. Stratification Indices

Three stratification indices were utilized in this study to assess the stratification conditions according to the measured salinity and SSC in an estuary: the salinity stratification parameter (N), the bulk/layer Richardson number, R_{iL}, and the gradient Richardson number, R_{ig}.

1. Salinity stratification parameter (N)

An acceptable definition of an estuarine stratification parameter based on the vertical structure of salinity proposed by Hansen and Rattray [40] is widely used. The parameter is a nondimensional index that can be defined as:

$$N = \frac{S_{bott} - S_{surf}}{S_m} \quad (1)$$

where S_{surf} and S_{bott} denote the salinity at the surface and bottom layers, respectively, and S_m is the average salinity between the surface and bottom layers ($=\frac{1}{2}(S_{surf} + S_{bott})$). Prandle [41] defined that when the stratification index (N) is less than 0.1, it represents a well-mixed water column. When the N value ranges between 0.1 and 1.0, the column is partially mixed. A water column with an N value greater than 1 is highly stratified in the presence of a salt wedge.

2. Bulk/layer Richardson number (R_{iL})

The velocity and density data were used to estimate the layered Richardson number (R_{iL}), quantitatively identifying the mixing condition through the water column. The number can be defined as follows.

$$R_{iL} = \frac{gh\left(\rho_{bott} - \rho_{surf}\right)}{\overline{u}^2\rho} \quad (2)$$

where ρ_{surf} and ρ_{bott} denote the water densities at the surface and bottom layers, respectively, h represents the water depth, g is the gravitational acceleration, $\overline{u}$ expresses the depth averaged velocity, and ρ denotes the water density containing salinity and suspended sediments (=$\rho_0 + 0.78$ S $+ 0.62$ C, $\rho_0 = 1000$ kg/m^3) [42]. When the R_{iL} value is less than 2, strong mixing occurs; when the R_{iL} value ranges between 2 and 20, it indicates a density interface that is modified by mixing; when the R_{iL} value is greater than 20, stable density stratification without mixing occurs [43].

3. Gradient Richardson number (R_{ig})

The gradient Richardson number, R_{ig}, is another parameter used to assess the state of mixing/stratification of a fluid. This parameter can be written as

$$R_{ig} = \frac{g\left(\frac{\partial \rho}{\partial z}\right)}{\rho\left(\frac{\partial u}{\partial z}\right)^2} \tag{3}$$

where $\frac{\partial \rho}{\partial z}$ denotes the vertical gradient of density and $\frac{\partial u}{\partial z}$ expresses the vertical gradient of horizontal velocity. Miles [44] and Geyer and Smith [45] recommended that when the R_{ig} value is greater than 0.25, a stable salinity stratification is present. When the R_{ig} value is less than 0.025, the water column tends to experience tidal mixing.

2.4. Barotropic and Baroclinic Modes

To examine the mechanics between incoming tide and river discharge, two terms affecting the water motion in the momentum balance equation, the barotropic and baroclinic pressure gradients, are explored. To evaluate the dominant term, barotropic and baroclinic pressure gradients must be separated to estimate their relative effect on the water motion. These two terms can be defined as follows:

$$\frac{1}{\rho_0}\frac{\partial p}{\partial x} = g\frac{\partial \eta}{\partial x} + \frac{g}{\rho_0}\left[\int_z^{\eta} \frac{\partial \rho}{\partial x} dz\right] \tag{4}$$

where x denotes the along-channel direction, z expresses the vertical direction, η represents the water surface elevation, and p is the water pressure. In Equation (4), the barotropic term is $g\frac{\partial \eta}{\partial x}$ and the baroclinic term is $\frac{g}{\rho_0}[\int_z^{\eta} \frac{\partial \rho}{\partial x} dz]$.

3. Results

3.1. Tidal Characteristics

Tidal dynamics play a crucial role in influencing the salinity and SSC at various temporal and spatial scales. Therefore, the tidal characteristics should be explored and analyzed first. According to the water level and discharge collected at the Guandu Bridge during low- and high-flow periods, the different tidal dynamics on 4 July 2106 and 17 July 2019 are illustrated in Figure 3. The duration during ebb tide was longer than that during flood tide, and the maximum ebb discharge was higher than the maximum flood discharge. The tidal asymmetry occurring during ebb and flood tides is caused by the interaction between the tidal effect and river flow [46]. The duration of ebb tide on 4 July 2016 was longer compared to that on 17 July 2019 because of the higher river flow.

The barotropic term (i.e., 4.14×10^{-4} m/s^2) was larger than the baroclinic term (i.e., 1.45×10^{-4} m/s^2) on July 4, 2016 during high flow, resulting in a longer ebb tide, while the barotropic term (i.e., 1.29×10^{-4} m/s^2) was smaller than the baroclinic term (i.e., 1.7×10^{-4} m/s^2) on 19 July 2019 during low flow, causing a relatively shorter ebb tide (Figure 3).

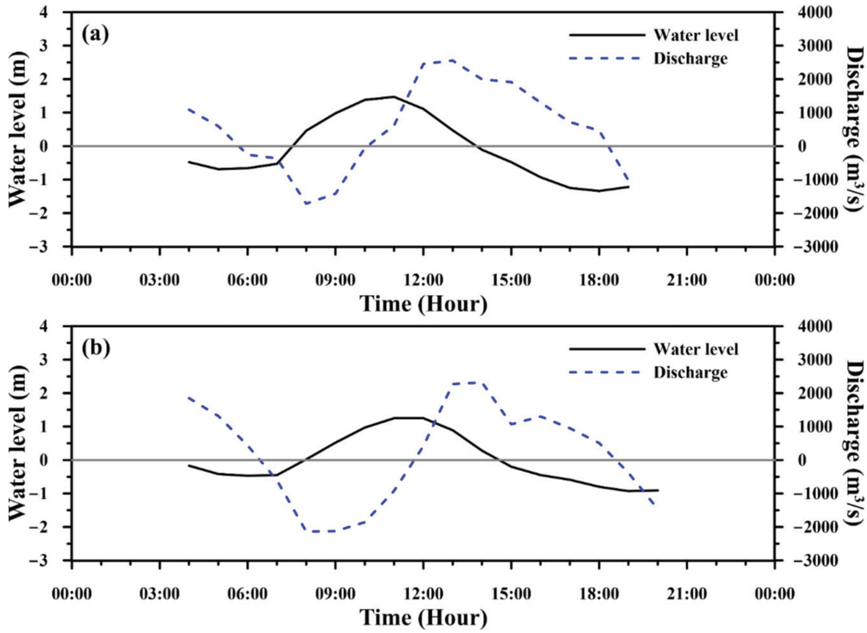


Figure 3. Water level and discharge at Guandu Bridge on (**a**) 4 July 2016, and (**b**) 17 July 2019. Note that the positive and negative discharges represent the flow downriver and upriver, respectively.

3.2. Salinity and Suspended-Sediment Concentration

The temporal variations in salinity and suspended-sediment concentration (SSC) on 4 July 2016 and 17 July 2019 for each measured station are illustrated in Figures 4 and 5, respectively. The figures show the vertically averaged concentrations of salinity and suspended sediment plus and minus one standard deviation for each measured time. The salinity during flood tide was higher than that during ebb tide in the downstream reaches, but the salinity was low during flood and ebb tides at the Xinhai Bridge, Zhongzheng Bridge, and Bailling Bridge resulting from the limit of saltwater intrusion. The time variation of salinity at the Taipei Bridge became low during high flow (Figure 4b) compared to its temporal variations during low flow (Figure 5b). This means that the high river flow pushed the limit of saltwater intrusion to further downstream. The time variation of salinity at the Guandu Bridge during high flow (Figure 4a) was also lower than that during low flow (Figure 5a).

In general, the time variation of SSC during high flow (Figure 4) was higher than that during low flow (Figure 5). The high flow induced more sediment resuspension from the bottom layer resulting in the higher SSC compared to the low flow. Furthermore, a high SSC was found in the downriver reaches compared to the upriver reaches. Because of tidal asymmetry, the suspended sediment migrates downstream and is transported to the open seas.

The vertical distributions of salinity and SSC at high slack tide at the Guandu Bridge and Taipei Bridge during high- and low-flow conditions are depicted in Figure 6. The vertical stratification of salinity at the Guandu Bridge at high slack tide during high flow compared to low-flow conditions (Figure 6a) is readily apparent. Partially mixed salinity occurred at the Taipei Bridge during low flow, and the salinity during high flow was lower than that during low flow (Figure 6b). Stratified conditions for SSC also appear at both the Guandu Bridge and Taipei Bridge during high- and low-flow conditions (Figure 6c,d). However, it should be noted that there was more stratification of SSC displayed at the bottom layer compared to the surface layer at Guandu Bridge (Figure 6c).

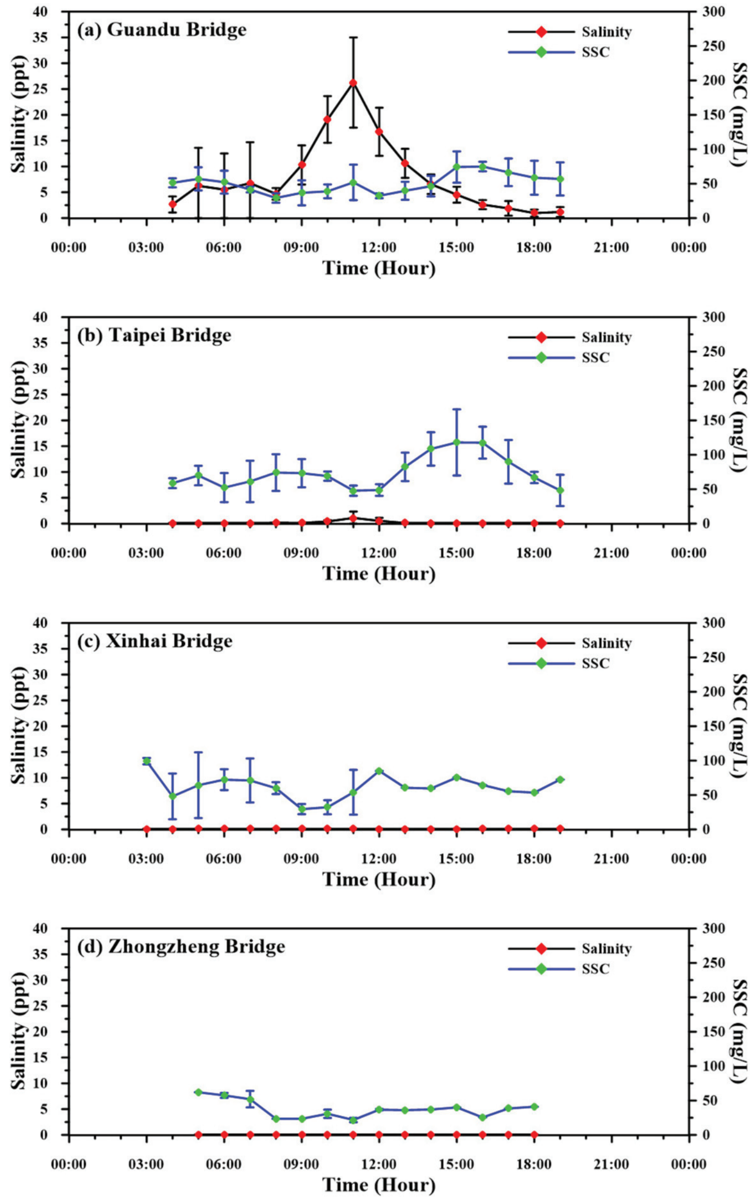


Figure 4. *Cont*.

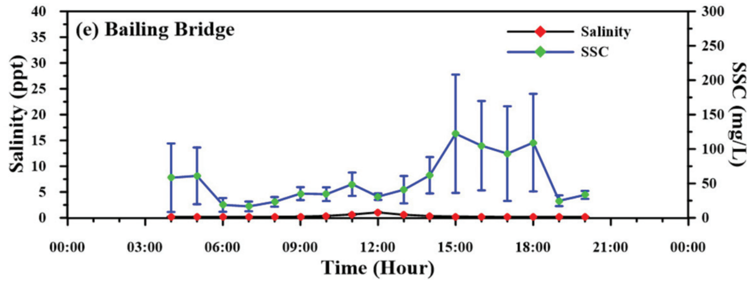
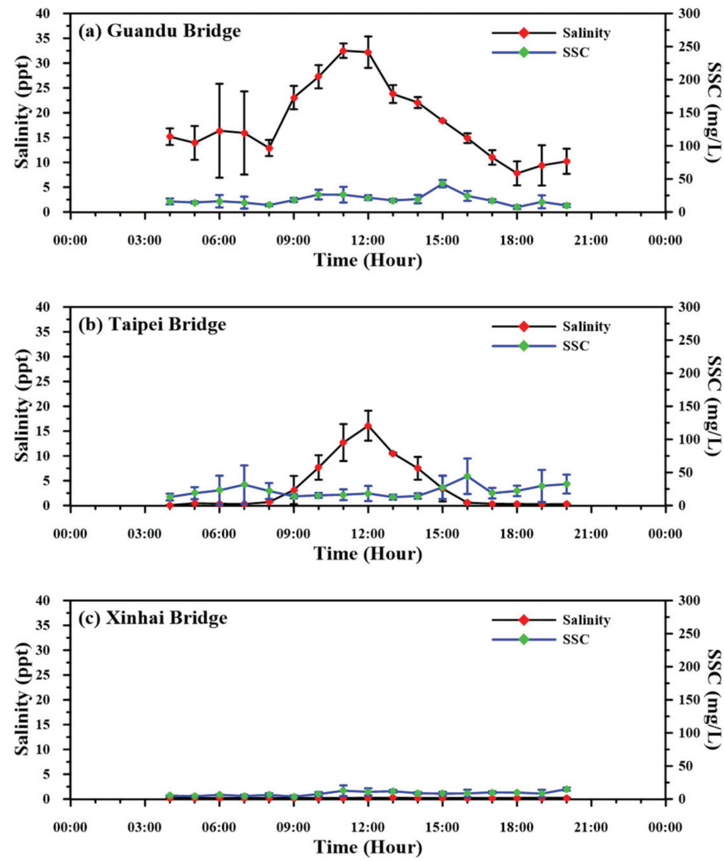


Figure 4. Salinity and suspended-sediment concentration on 4 July 2016, at (**a**) Guandu Bridge, (**b**) Taipei Bridge, (**c**) Xinhai Bridge, (**d**) Zhongzheng Bridge, and (**e**) Bailing Bridge. The mean value ± one standard deviation for each measured time is shown.



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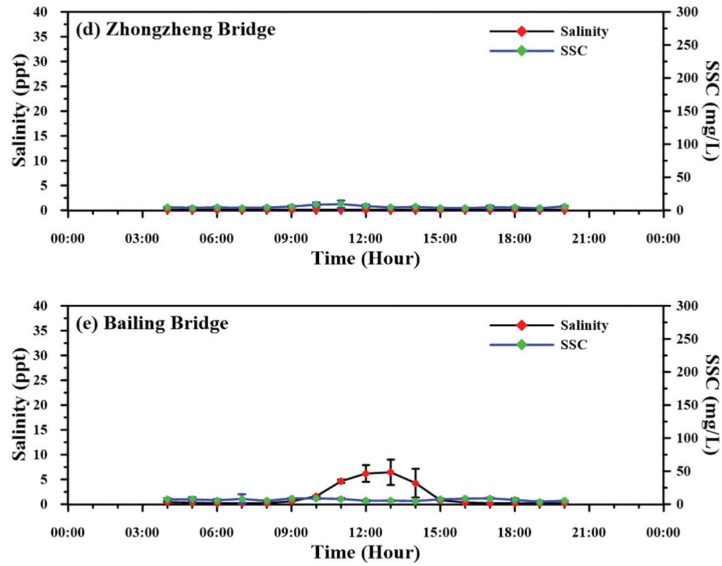
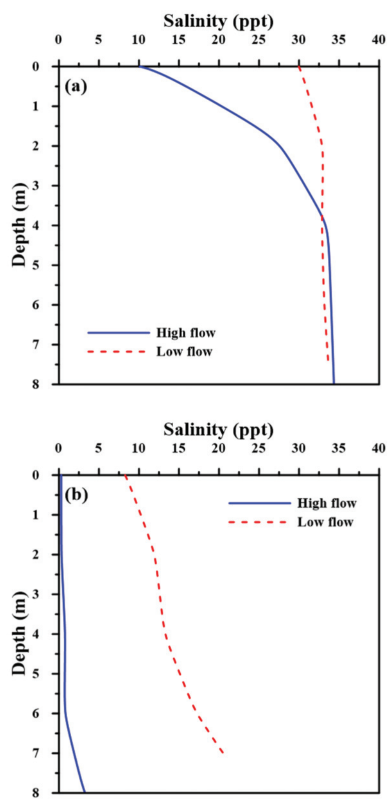


Figure 5. Salinity and suspended-sediment concentration on 17 July 2019 at (**a**) Guandu Bridge, (**b**) Taipei Bridge, (**c**) Xinhai Bridge, (**d**) Zhongzheng Bridge, and (**e**) Bailing Bridge. The mean value ± one standard deviation for each measured time is shown.



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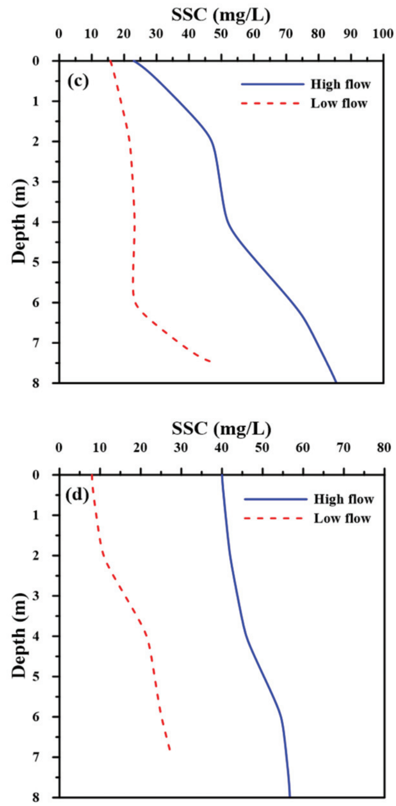

Figure 6. Vertical distributions of (**a**,**b**) salinity and (**c**,**d**) SSC during high- and low-flow conditions at high slack tide at (**a**,**c**) Guandu Bridge and (**b**,**d**) Taipei Bridge.

3.3. Stratification Variability

To comprehend the stratification variations in tidal estuaries, three related parameters, N, R_{iL}, and R_{ig}, were determined. Figures 7 and 8 depict the time variation of these parameters on 4 July 2016 and 17 July 2019, respectively. According to the stratification criteria displayed in Figure 7, conditions mostly stayed between stratification and partially mixed at the Guandu Bridge and exhibited good mixing at the Taipei Bridge during high flow. During low flow (Figure 8), conditions were mostly between partially mixed and well-mixed at the Guandu Bridge and Taipei Bridge.

The salinity stratification parameter (N) utilizes the vertical salinity profile to judge the stratification state in the water column. This parameter is simple but does not consider the contribution of the suspended-sediment concentration. The gradient Richardson number is very sensitive to the interval of vertical measurement and the accuracy of velocity; therefore, a small deviation in velocity causes a huge range of R_{ig} values [43]. Compared to N and R_{ig}, the bulk/layer Richardson number, R_{iL}, is more practical for examining the stratification variability.

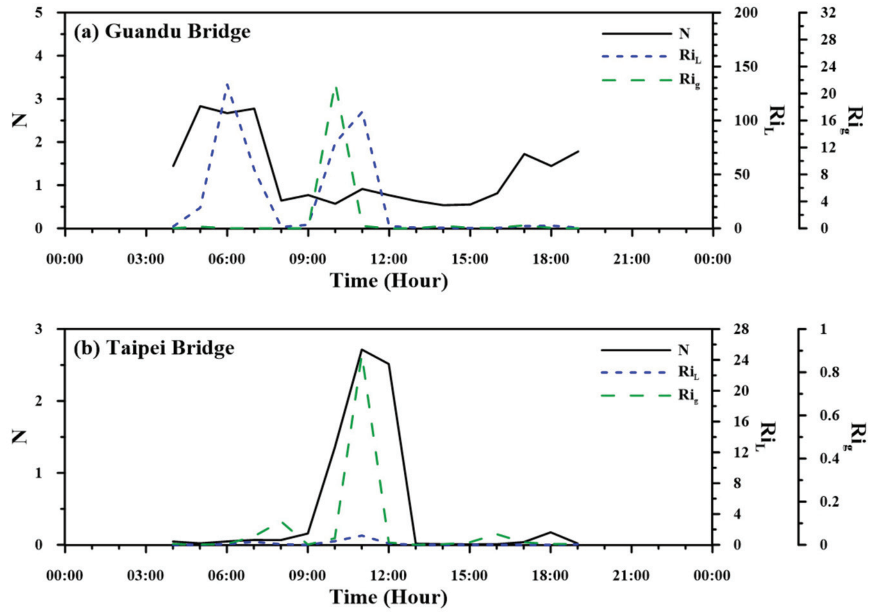

Figure 7. Temporal variations in stratification parameters on 4 July 2016 at (**a**) Guandu Bridge and (**b**) Taipei Bridge.

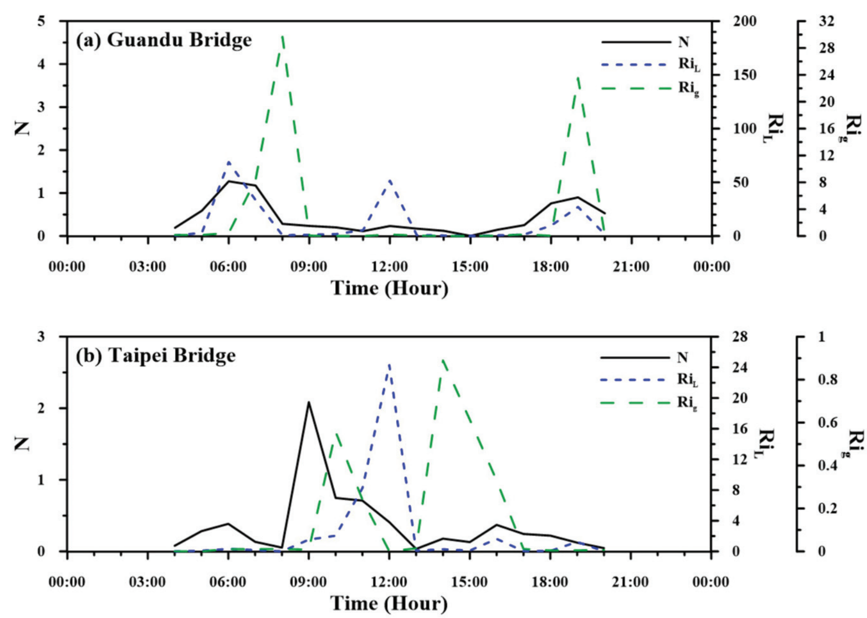

Figure 8. Temporal variations in stratification parameters on 17 July 2019 at (**a**) Guandu Bridge and (**b**) Taipei Bridge.

4. Discussion

4.1. Estuarine Circulation and Mixing Conditions

According to the modeling results reported by Hsu et al. [37] and Liu [47], estuarine circulation was found in the lower reaches of the tidal estuarine zone and depended on the river discharges. The estuarine circulation usually occurred at Guandu Bridge, which has a deep channel at approximately 11 m and was also displayed at the Taipei Bridge during low flow. Based on the time-series variations in salinity during high- and low-flow conditions (Figures 4 and 5), we inferred that estuarine circulation occurred at the Guandu Bridge during both flow conditions but did not occur during high-flow conditions at the Taipei Bridge.

A reduction in vertical mixing led to extended salinity-induced stratification during low flow, as denoted by the stratification parameter (N) and bulk/layer Richardson number (R_{iL}) in Figures 7 and 8. Such salinity-induced stratification defines the occurrence of estuarine circulation. The well-mixed condition clearly occurred at the Taipei Bridge during high flow (Figures 6b and 7b).

4.2. Longitudinal Changes in Salinity and SSC

To easily examine the longitudinal changes in salinity and SSC along the channel, the time-series variations in salinity and SSC along the channel are depicted in Figures 9 and 10, respectively. The vertical salinity variations over time displayed stratification during low flow at the Guandu Bridge and Taipei Bridge compared to the high-flow condition. Except for the Guandu Bridge and Taipei Bridge, the other stations exhibited a well-mixed state. The salinity during flood tide was higher than that during ebb tide (Figure 9). A high SSC was also found in the downstream reaches during high flow compared to the SSC along the channel during low flow. The SSC during ebb tide was higher than that during flood tide in the lower reaches (Figure 10). However, the flood–ebb and river discharge dominated the saltwater intrusion along the channel, while the river discharge conspicuously controlled the SSC.

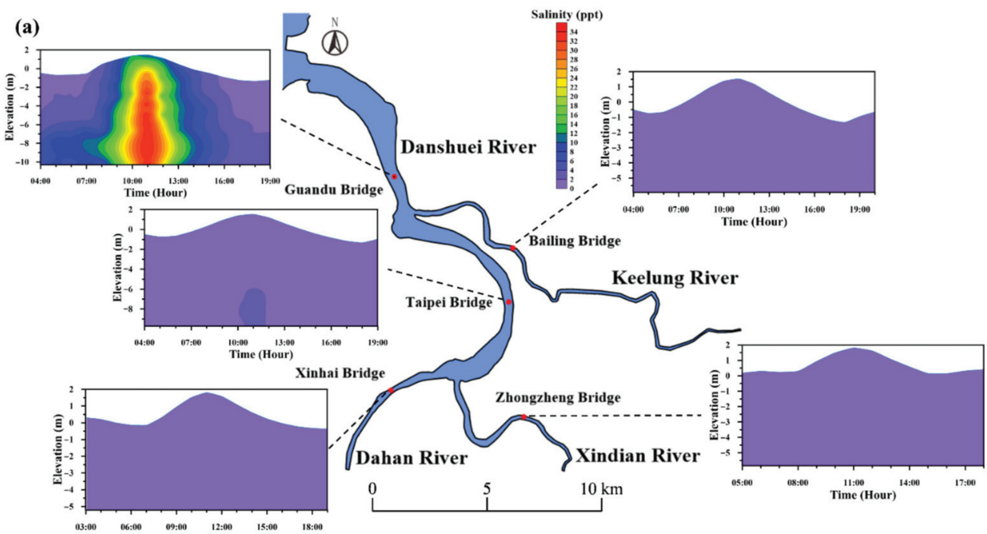

Figure 9. *Cont.*

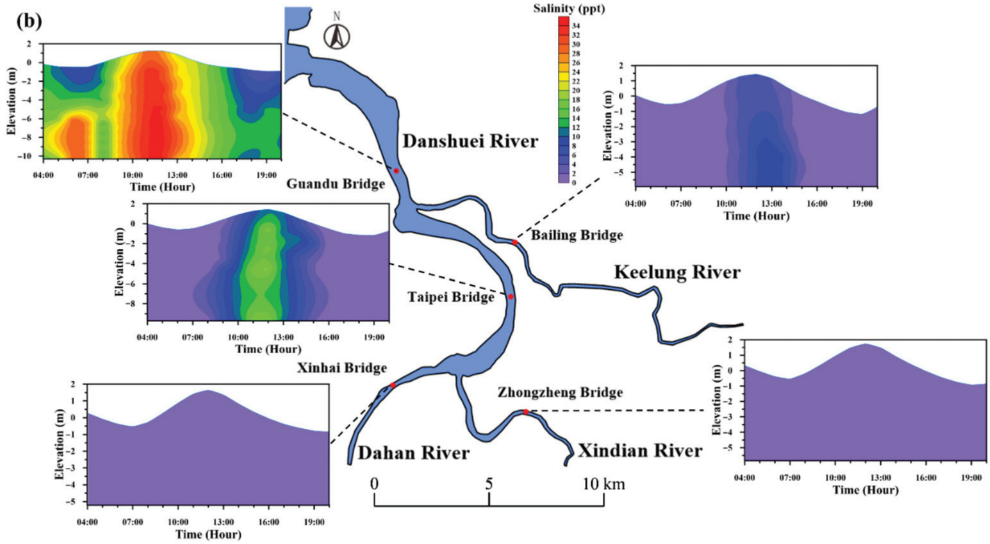

Figure 9. Time-series variations in salinity along the channel on (**a**) 4 July 2106 and (**b**) 17 July 2019.

Several reports have documented that the incoming tide, river discharge, near-bed water velocities, sediment grain size, and waves affect the suspended-sediment concentration in tidal estuaries [32,48–51]. The wave effect on SSC in the Danshuei River estuary can be negligible because of the barrier of the mountain. The near-bed velocity controls sediment erosion, and grain size affects sediment deposition. However, these two factors are not considered in this study. Due to the tidal asymmetry dominated by ebb velocity, the net suspended-sediment transport was landward [52]. According to the measured results displayed Figures 6c and 10, the estuarine turbidity maximum would appear at the bottom layer of the Guandu Bridge because of local deepening of the bed [35].

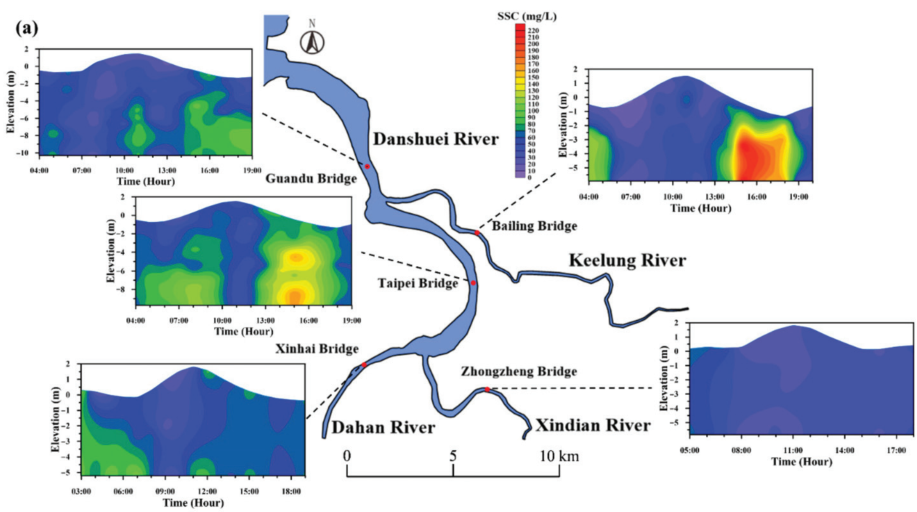

Figure 10. *Cont.*

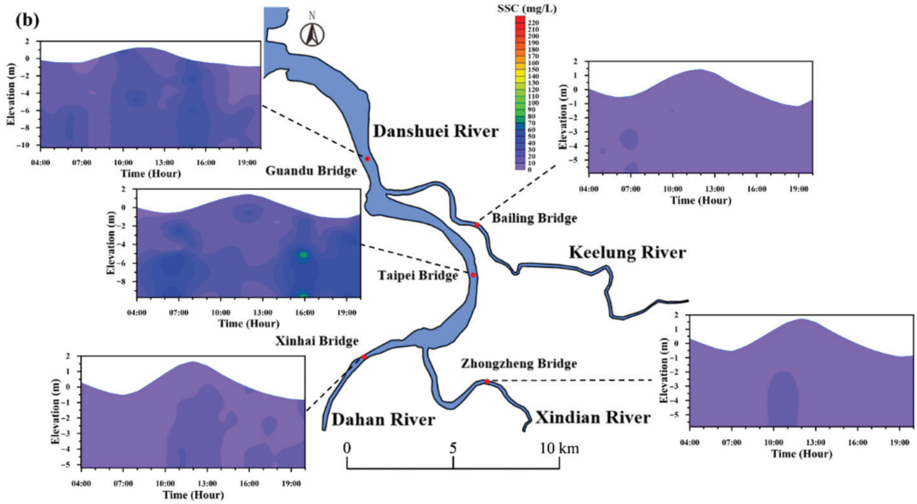

Figure 10. SSC time-series variations along the channel on (**a**) 4 July 2016 and (**b**) 17 July 2019.

4.3. Possibility of Modeling and Future Work

Model simulations using the observed salinity and SSC in tidal estuaries can assist researchers in understanding sediment dynamics [53,54]. The suspended-sediment transport in the models was greatly determined by bed erosion and sediment resuspension. The so-called erosion-limited approach considers bed erosion and sediment resuspension to be closely related to bed shear stress. An additional factor affecting SSC is the settling velocity, which results from flocculation processes [31,55–57]. These fundamental factors may be considered in the modeling process to reflect sediment transport and dynamics.

The SSC in the Danshuei River estuary was only on the scale of tens to hundreds of mg/L. However, the high concentration of suspended sediment in the lower estuarine zone would have an impact on water quality and ecosystems, so it is in the process of model development. To achieve the goal of integrating observational data and models, it is necessary to couple hydrodynamic, water quality, and ecological models to refine the temporal and spatial resolutions. Cross-disciplinary researchers would join the model development to participate in future research and discussion.

5. Conclusions

The distribution of salinity and suspended sediment in tidal estuaries is affected by different interrelated factors. The relative importance of each factor is difficult to quantify, partly because of the lack of observation and partly because of the complex nature of the processes and the coupling among them. However, as a conservative quantity, exploring the salinity distribution is easier than comprehending the more complex and dynamic distribution of suspended sediment.

The study presents the results of intensive surveys of salinity and suspended sediment in the Danshuei River estuary during high- and low-flow conditions. The salinity at the Guandu Bridge exhibited good mixing during low flow and stratification during high flow at high slack tide. The salinity was low at both flood and ebb tides at the Xinhai Bridge, Zhongzheng Bridge, and Bailling Bridge resulting from the limit of saltwater intrusion. The high freshwater discharges resulted in lower salinity because barotropic forcing dominated, while the low freshwater discharges caused higher salinity and longer saltwater intrusion because baroclinic forcing dominated. According to the stratification indices, the results revealed that mostly partial mixing occurred at the Guandu Bridge and good mixing occurred at the Taipei Bridge during high flow, while mostly partial mixing and good mixing occurred at both the Guandu Bridge and Taipei Bridge during low flow.

A high SSC was found in the downstream reaches during high flow compared to the SSC along the channel during low flow. The SSC during ebb tide was higher than that during flood tide in the lower reaches. The results indicated that river discharge obviously controlled the SSC in tidal estuaries. Based on two intensive surveys, an estuarine turbidity maximum occurred at the bottom layer of Guandu Bridge resulting from the local deepening reaching 11 m. The processes affecting SSC on different spatial and temporal scales remain complex and worth exploring. Further work will focus on the improvement of measurement techniques and model development.

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Institutional Review Board Statement: This study did not require ethical approval.

Informed Consent Statement: Not applicable.

Data Availability Statement: The measured data are subject to request.

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Conflicts of Interest: The authors declare no conflict of interest.

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standards

Article

Visualization Concept of Automotive Quality Management System Standard

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Abstract: In organizations that manufacture products or provide services as well as in academic practice, the visualization of management systems' standards is presented primarily in the form of static diagrams or tables. Demands for the quality of products and services are reflected in the complexity and interconnectedness of standards, which could cause complications during the implementation phase. This article presents a visualization of the standard *IATF 16949 Automotive Quality Management System Standard, Quality management system requirements for automotive production and relevant service parts organizations*, which incorporates in its content *ISO 9001 Quality Management Systems—Requirements* using a dynamic cluster model built using software TouchGraph Navigator. The visualization process began with a detailed examination of the two-stage requirements, documented information, and notes detailed in *IATF 16949* and continued with the creation of a central node to which new nodes were subsequently connected, containing the introductory parts of the standard, including clauses. The activation of clauses and sub-clauses for other parts of the document followed. The dynamic behavior of the resulting cluster can be used in the implementation, execution, maintenance, or certification process to encourage organizations to improve their operational processes by incorporating more rigorous quality considerations into their operational frameworks.

Keywords: visualization; cluster; IATF 16949; ISO 9001; automotive industry; management system; standard; management system standards

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1. Introduction

The reason why it is worth visualizing standards is derived from the needs of all stakeholders. Stakeholders relevant to the management system are those who are in any way influenced by the system or constitute a part of its operation, e.g., shareholders, creditors, stock investors, suppliers, employees, customers, or local communities. Typically, they all have different interests in the company. The importance of understanding their expectations and requirements is best known to those who deal with the implementation of management systems and their associated standards within the company. The implementors are responsible for and required to have a detailed understanding of what the standard deals with, its scope, structure or the number of levels of a structure, or how the standard intends to help establish, maintain, and improve management systems.

Standards can be, by default, quite complicated to work with correctly. One can use graphics to make them more understandable, but that is not sufficient. Graphics on their own are also insufficient, they are part of a whole. They complement the text and are complemented by the text [1]. Hence, there is a search for a synergy between text and graphics, where one can retrieve the text related to the graphic information instantaneously and move fluently within the standard. Visualization provides such a solution and at the same time communicates the purpose behind the process.

Technical and management standards are not frequently visualized in industrial practice. The standard use could be found in terms of pure data/value visualization, but not as data/text visualization. The transition from a paper-based approach to visualization is not simple. Becoming visual requires many skills. One needs to know how to process and mine data to identify findings, generate presentation quality graphics, and communicate outcomes to the target audience [2]. In this case the targeted audience are people directly working with management systems.

It is crucial for managers, as internal stakeholders, to have the ability to navigate as quickly and as clearly as possible within the standard, and its individual clauses. It is not appropriate for them either to fumble and thus sabotage the implementation of a management system during the implementation stage, or, during the maintenance stage, if the system is in place and needs regular care to work correctly.

Visualization is a kind of storyline that gives a clear answer to a question without necessary details. By focusing on the original intent of the question, you can eliminate such details because the question provides a benchmark for what is and is not necessary [3].

Many people who are involved in the various stages of the lifecycle of the management system adhere strictly to the Plan-Do-Check-Act (PDCA) cycle or, more effectively, to the Plan-Do-Study-Act (PDSA). PDSA was originally designed by Deming [4], and supporters of this type of cycle are more aware of the complexity and scope of the management system if they do not look at it “classically.” Classically, or conventionally, means that they have the document (standard) in question in their hands or on the monitors and in order to locate the information they need to look for it manually. “Non-classical” means that they have a visualized dynamic cluster available that is alive, and one click brings immediate results. In such an unconventional representation, the proverb that “It is better to see once than to hear three times” is valid.

1.1. Visualization Management

The Moravian pedagogue Jan Amos Komenský, who also supported visualization as a didactic means of acquiring knowledge, has clearly stated that, “There is nothing in reason that was not in the senses before” [5]. Thus, visualization will help to ensure that the standard makes its way effectively through the eyes to the mind of the stakeholder.

People, or stakeholders, are constantly looking for a way to identify new information. They try to find them as quickly as possible. The reason we want to be better informed is so that we can make better decisions. Research shows that visualized information is faster and easier to understand and is much more likely to be remembered by people [6].

It is not easy to define what visualization means and how to “grasp” this concept intellectually. Some authors are considering information visualization because visualization can also be multimodal, that is, composed of both textual and visual elements such as lines, shapes, icons, or background images. These elements are then used to organize information visually [7].

Other authors understand visualization as a process of graphically representing data or information. Here, the visualization itself provides encoded relationships, patterns, similarities, and differences through shape, color, position, and size. These visual representations of the data can make findings and ideas stand out. Data visualization is a basic skill in our modern, data-driven world. Almost every aspect of our daily routine generates data: the steps we take; the movies we watch; the products we buy; and the conversations we lead. Much of this data from our digital “exhaust” is stored, waiting for someone to make sense of it [8].

The abbreviation “infovis” stands for information visualization, but it is not easy to define the MSS visualization in such a way that it is applicable to all projects and can be distinguished from other related areas such as scientific visualization or information design. The preliminary definition includes a mapping between discrete data and the representation visual [2].

1.2. Management Systems Standards Suitable for Clustering

Management system visualization means the ability to create a dynamic cluster for any MSS, which can then be merged with other clusters into one multi-cluster through interconnections and thus integrate management systems. One such larger cluster already available is a visualized integrated model for up to three standards: ISO 9001 QMS (Quality), ISO 14001 EMS (Environment), and ISO 20121 SEMS (Sustainability Events) [9] or a single small cluster dedicated to only one standard, ISO 46001 WEMS (Water Efficiency) [10].

Currently, 98 management systems are defined in standards by the *International Automotive Task Force and International Organization for Standardization* as well as alternative standards in the International Workshop Agreement (IWA). The International Workshop Agreement is one of several working alternatives to ISO international standards where the rapid development and publication of a document is a priority. Compared to the usual ISO process of developing international standards through a technical commission structure, IWA documents are developed in open workshops and organized by the National Standards Institute. The documents are approved by consensus between the participants in these workshops [11].

The list of standards is constantly being expanded to include new management systems that have a harmonized structure (HS). The standards, which are registered under the list of management standards as HS, have the same structure and contain many of the same terms and definitions as the "Consolidated ISO Supplement". This harmonized label is particularly useful for those organizations that choose to operate a single management system that can meet the requirements of two or more management system standards simultaneously [12,13].

The standards revised since 2015 have a high level of structuring (HLS), which means that the standards arranged in this way provide the same structure, text, and common terms and definitions for all future MSS ISOs. In this way, all ISO management systems' standards can be harmonized to facilitate the full integration of multiple standards into a single management system for operation in a single organization [14].

2. Materials and Methods

The key goal of this work was to create a cluster for a specific single standard called IATF 16949, which belongs to an organization with international operations, whose abbreviation and designation of the standard are identical [15].

2.1. Automotive Quality Standards

IATF is a global technical specification and quality management standard for the automotive industry. Based on the standard ISO 9001:2015, it was published in October 2016 and replaces standard ISO/TS 16949. It is designed to be used in conjunction with standard ISO 9001:2015 and includes supplementary requirements specific for the automotive industry rather than being a standalone QMS. IATF combines standards from across Europe and the U.S. IATF 16949:2016 outlines everything you need to know about achieving best practice when designing, developing, manufacturing, installing, or servicing automotive products [16].

IATF organization is developed for that purpose by a group of automobile manufacturers and their related national associations of the automotive industry with the aim of providing the customers in the automotive industry with high quality products.

Following is a list of specific purposes for which the IATF was established:

- To develop a consensus regarding international fundamental quality system requirements, primarily for the participating companies' direct suppliers of production materials, products, or service parts or finishing services (e.g., heat treating, painting, and plating). These requirements will also be available for other interested parties in the automotive industry;
- To develop policies and procedures for the common IATF third party registration scheme to ensure consistency worldwide;

- To provide appropriate training to support IATF 16949 requirements and the IATF registration scheme;
- To establish formal liaisons with appropriate organizations to support the goals of IATF [17].

The history of IATF 16949 is somewhat complicated, as it was developed by two organizations simultaneously, although with the same goal. That was to create a standard that would ensure quality in the automotive industry specifically. It embodies ISO 9001, which is a generic standard for the assessment of quality management systems. It is not a product standard. ISO/TS 16949 does not contain requirements with which a product or a service can comply. There are no product acceptance criteria in ISO/TS 16949, so you cannot inspect a product against the standard [18]. Thus, while the original ISO/TS 16949 addresses only the organization's requirements, IATF 16949 also includes specifications and customer requirements in the audit to determine whether the service organization or product organization meets them [19].

We can find the answer to the question why two manuals are there, IATF 16949:2016 and ISO 9001:2015, to address the same issue, in the IATF document 16949:2016 FAQ, revised and reissued in April 2021. The IATF and ISO were simply not able to reach a licensing agreement to publish IATF 16949 in an integrated document. In order to not further delay the launch of the new IATF 16949 standard, the IATF decided to publish it in a two-manual format. Prior to release, the IATF confirmed with international accreditation organizations that other industry sectors use a two manual format model to define their sector specific requirements, and auditing with the two manual model, while not optimal, is effective. The IATF maintains strong cooperation with ISO by continuing the liaison committee status, ensuring continued alignment with ISO 9001 [20].

IATF 16949 could therefore be characterized as two standards in one. We could also label it as a superstructure because ISO 9001 QMS forms the basis—the so-called "golden core" of the management system in IATF 16949. Compared to the two management systems, we can say that the IATF is a much more rigorous standard than ISO 9001, which is generally more widely applicable to all organizations that offer services or manufacture products. In addition, the QMS standard includes another ISO 9000 standard, which deals with management system terminology [21,22].

A topic that is often discussed is the connection between IATF 16949 and ISO 9001. According to a study conducted by Laserukin-Iturbea at al. the findings show that IATF 16949 adds value to a more flexible ISO 9001 in five main areas: market, customer service in the supply chain, operational performance, staff, and technology [23]. Overall, IATF 16949 is seen as a 'license to operate' for automotive sector suppliers, for whom ISO 9001 seems to have lost its signaling value. The rigor of IATF 16949 is also evident from the number of revisions in a given time interval. The revisions concern in particular the binding interpretations of the individual articles of the standard, because the binding interpretations change the interpretation of the rules or requirements, and the latter itself becomes a disagreement (non-compliance). The first edition of IATF 16949 was published in English in October 2016 and entered into force on 1 January 2017. The first revision has been in force since October 2017 and there is currently a fifth edition containing 22 revisions valid from November 2021 [24]. On the other hand, the ISO 9001:2015 standard shows greater resistance because it was last revised and validated in May 2021, while the original version of the standard remains current.

As part of continuing support, the IATF organization published the fifth edition in February 2021 of FAQs for certification organizations and interested parties, in order to improve the understanding of existed requirements [20].

Based on the above, we are of the opinion that it is significantly necessary to facilitate the orientation of interested parties in the discussed standard IATF 16949 and the subsequent understanding of its requirements. Another support tool (outside the IATF organization) appears to be the creation of a visualized concept of a quality management system standard in the automotive industry using a software application that allows, in addition to the desktop use, also a presentation on a web platform. This concept should help managers working in organizations producing series production and production of relevant components in the automotive industry to fully meet the requirements of stakeholders and facilitate first-, second- and third-party audits at a higher level. The amount of work involved in developing the concept is significant only at the beginning, the incorporation of *Sanctioned Interpretations* (IATF 16949) can be completed on an ongoing basis as revisions are issued.

As already mentioned, the other materials used for the concept development are the ISO 9001 and ISO 9000 standards. They represent an integral part and without them it is not possible to develop the given cluster correctly. The Supplementary Materials were already discussed in detail in the following article: "Innovative Approaches to Model Visualization for Integrated Management Systems" [9].

2.2. Methodology of Visualization

To create a cluster using visualization, it is necessary to emphasize that visualization is not just an image that at first glance presents its content, but it is a smart project that captures the essence, has a descriptive value, and is dynamic. Visualization is used to present project models for spatial networks, hierarchical structures, relationships, interactions, and communities. The process of visualizing the cluster follows the following procedure:

- Selection of a data set, which can also be completed by importing data from an external database, their correct filtering and data transformation, which is performed if we do not have the data in the required form and it is necessary to transform it;
- Defining individual nodes or cells of the cluster and graphical differentiation according to selected criteria, whether using the size, shape, color, or other attribute of the node;
- Defining individual edges between the nodes and, again, graphical differentiation in terms of thickness, format, color, etc.;
- Control of the interaction correctness;
- Research and further study of the cluster.

However, there are many formats available for storing data, and a large number of generic or specialized software applications for cluster networking and analysis. Many software packages are available in paid format, as a volume license for academic processes, or as open-source programs.

To develop a visualized concept of the Automotive Quality Standards, TouchGraph Navigator software was used. It enables the generation of interactive network visualizations of existing data that could be retrieved from the Excel (.xls) database.

In a given computer application, it is possible to analyze and variously visualize individual connections in a cluster, export visualizations to .pdf, png and .jpg formats and export the data to Table Data (Excel MS), Graph, or Merged Graph (Vna) formats [25]. This software is also used in the author's workplace, where several large-scale projects related to legislation and MSS have already been built based on it.

To create a data set for MSS visualization of the IATF 16949 standard in the TouchGraph Navigator application, the data file must be compiled correctly. For convenience, only one sheet of the Excel file was used for the cluster, in which detailed data contained in IATF 16949 were edited and specially arranged. These data include the structure of the standard with its clauses, individual management system requirements, documented information, and notes for further explanation of the MSS. A total of 276 rows and a range of A-AC columns were used. Because IATF 16949 is a paid document and is not publicly available, the AC column is edited as an example only, for illustration. This file serves as a database for our network visualization of the MSS cluster.

3. Results

Based on a detailed examination of the common and specific requirements, documented information and notes for IATF 16949, Table 1 has been derived. The table shows the assignment of clauses to the PDCA cycle phases for ISO 9001. The other clauses contained in the IATF 16949 extension standard are shown in bold.

Table 1. Phases of PDCA Cycle management system according to IATF 16949 (Source: author).

Phase of PDCA Cycle	ISO 9001 (Base) and IATF 16949 (Extension/Supplemental)
	0 Introduction
	0.1 General
	0.2 Quality management principles
	0.3 Process approach
	0.3.1 General
	0.3.2 Plan-Do-Check-Act cycle
	0.3.3 Risk-based thinking
	0.4 Relationship with other MSSs [1]
	1 Scope
	1.1 Scope—automotive supplemental to ISO 9001:2015
	2 Normative references
	2.1 Normative and informative references
	3 Terms and definitions
	3.1 Terms and definitions for the automotive industry
	4 Context of the organization
	4.1 Understanding the organization and its context
I. phase: PLAN	4.2 Understanding the needs and expectations of interested parties
I. phase: PLAN	4.3 Determining the scope of the QMS [2]
	4.3.1 Determining the scope of the QMS—supplemental
	4.3.2 Customer-specific requirements
	4.4 Quality management system and its processes
	4.4.1
I. phase: PLAN	**4.4.1.1 Conformance of product and processes**
I. phase: PLAN	**4.4.1. 2 Product safety**
	4.4.2
	5 Leadership
	5.1 Leadership and commitment
	5.1.1 General
	5.1.1.1 Corporate responsibility
	5.1.1.2 Process effectiveness and efficiency
	5.1.1.3 Process owners
	5.1.2 Customer focus
I. phase: PLAN	5.2 Policy
I. phase: PLAN	5.2.1 Establishing the quality policy
I. phase: PLAN	5.2.2 Communicating the quality policy
I. phase: PLAN	5.3 Organizational roles, responsibilities, and authorities
I. phase: PLAN	**5.3.1 Organizational roles, responsibilities, and authorities—supplemental**
I. phase: PLAN	**5.3.2 Responsibility and authority for product requirements and corrective actions**
All clauses No. 6—I. phase: PLAN	6 Planning
	6.1 Actions to address risks and opportunities
	6.1.1
	6.1.2
	6.1.2.1 Risk analysis
	6.1.2.2 Preventive action
	6.1.2.3 Contingency plans
	6.2 Quality objectives and planning to achieve them
	6.2.1
	6.2.2
	6.2.2
	6.2.2.1 Quality objectives and planning to achieve them—supplemental
	6.3 Planning of changes

Table 1. *Cont.*

Phase of PDCA Cycle	ISO 9001 (Base) and IATF 16949 (Extension/Supplemental)
All clauses No. 7—II. phase: DO	7 Support 7.1 Resources 7.1.1 General 7.1.2 People 7.1.3 Infrastructure **7.1.3.1 Plan, facility, and equipment planning** 7.1.4 Environment for the operation of processes **7.1.4.1 Environment for the operation of processes—supplemental** 7.1.5 Monitoring and measuring resources 7.1.5.1 General **7.1.5.1.1 Measurement system analysis** 7.1.5.2 Measurement traceability **7.1.5.2.1 Calibration/verification records** **7.1.5.3 Laboratory requirements** **7.1.5.3.1 Internal laboratory** **7.1.5.3.2 External laboratory** 7.1.6 Organizational knowledge 7.2 Competence **7.2.1 Competence—supplemental** **7.2.2 Competence—on-the-job** **7.2.3 Internal auditor competency** **7.2.4 Second-party auditor competency** 7.3 Awareness **7.3.1 Awareness—supplemental** **7.3.2 Employee motivation and empowerment** 7.4 Communication 7.5 Documented information 7.5.1 General **7.5.1.1 Quality management system documentation** 7.5.2 Creating and updating 7.5.3 Control of documented information 7.5.3.1 7.5.3.2 **7.5.3.2.1 Record retention** **7.5.3.2.2 Engineering specifications**
All clauses No. 8—II. phase: DO	8 Operation 8.1 Operational planning and control **8.1.1 Operational planning and control—supplement** **8.1.2 Confidentiality** 8.2 Requirements for products and services 8.2.1 Customer communication **8.2.1.1 Customer communication—supplemental** 8.2.2 Determining the requirements for products and services **8.2.2.1 Determining the requirements for products and services—supplemental** 8.2.3 Review of the requirements for products and services 8.2.3.1 **8.2.3.1.1 Review of the requirements for products and services—supplemental** **8.2.3.1.2 Customer-designated special characteristics** **8.2.3.1.3 Organization manufacturing feasibility** 8.2.3 Review of the requirements for products and services 8.2.4 Changes to requirements for products and services 8.3 Design and development of products and services 8.3.1 General **8.3.1.1 Design and development of products and services—supplemental** 8.3.2 Design and development planning **8.3.2.1 Design and development planning—supplemental** **8.3.2.2 Product design skills** **8.3.2.3 Development of products with embedded software**

Table 1. *Cont.*

Phase of PDCA Cycle	ISO 9001 (Base) and IATF 16949 (Extension/Supplemental)
	8.3.3 Design and development inputs **8.3.3.1 Product design and development inputs** **8.3.3.2 Manufacturing process design input** **8.3.3.3 Special characteristics** 8.3.4 Design and development controls **8.3.4.1 Monitoring** **8.3.4.2 Design and development of validation** **8.3.4.3 Prototype program** **8.3.4.4 Product approval process** 8.3.5 Design and development outputs **8.3.5.1 Design and development outputs—supplemental** **8.3.5.2 Manufacturing process design output** 8.3.6 Design and development changes **8.3.6.1 Design and development changes—supplemental** 8.4 Control of externally provided processes, products and services 8.4.1 General **8.4.1.1 General—supplemental** **8.4.1.2 Supplier selection process** **8.4.1.3 Customer-directed sources (also known as "Directed-Buy")** 8.4.2 Type and extent of control **8.4.2.1 Type and extent of control—supplemental** **8.4.2.2 Statutory and regulatory requirements** **8.4.2.3 Supplier quality MS development** **8.4.2.3.1 Automotive product-related SW or automotive products with embedded SW** **8.4.2.4 Supplier monitoring** **8.4.2.4.1 Second-party audits** **8.4.2.5 Supplier development** 8.4.3 Information for external providers **8.4.3.1 Information for external providers—supplemental** 8.5 Production and service provision 8.5.1 Control of production and service provision **8.5.1.1 Control plan** **8.5.1.2 Standardized work—operator instructions and visual standards** **8.5.1.3 Verification of job set-ups** **8.5.1.4 Verification after shutdown** **8.5.1.5 Total productive maintenance** **8.5.1.6 Management of production tooling and manufacturing, test, inspection tooling and equipment** **8.5.1.7 Production scheduling** 8.5.2 Identification and traceability **8.5.2.1 Identification and traceability—supplemental** 8.5.3 Property belonging to customers or external providers 8.5.4 Preservation **8.5.4.1 Preservation—supplemental** 8.5.5 Post-delivery activities **8.5.5.1 Feedback of information from service** **8.5.5.2 Service agreement with customer** 8.5.6 Control of changes **8.5.6.1 Control of changes—supplemental** **8.5.6.1.1 Temporary change of process controls** 8.6 Release of products and services **8.6.1 Release of products and services—supplemental** **8.6.2 Layout inspection and functional testing** **8.6.3 Appearance items** **8.6.4 Verification and acceptance of conformity of externally provided products and services** **8.6.5 Statutory and regulatory conformity** **8.6.6 Acceptance criteria**

Table 1. *Cont.*

Phase of PDCA Cycle	ISO 9001 (Base) and IATF 16949 (Extension/Supplemental)
	8.7 Control of nonconforming 8.7.1 **8.7.1.1 Customer authorization for concession** **8.7.1.2 Control of nonconforming product—customer-specified process** **8.7.1.3 Control of suspect product** **8.7.1.4 Control of reworked product** **8.7.1.5 Control of repaired product** **8.7.1.6 Customer notification** **8.7.1.7 Nonconforming product disposition** 8.7.2
All clauses No. 9—III. phase CHECK	9 Performance evaluation 9.1 Monitoring, measurement, analysis and evaluation 9.1.1 General **9.1.1.1 Monitoring and measurement of manufacturing processes** **9.1.1.2 Identification of statistical tools** **9.1.1.3 Application of statistical concepts** 9.1.2 Customer satisfaction **9.1.2.1 Customer satisfaction—supplemental** 9.1.3 Analysis and evaluation **9.1.3.1 Prioritization** 9.2 Internal audit 9.2.1 9.2.2 **9.2.2.1 Internal audit program** **9.2.2.2 QMS audit** **9.2.2.3 Manufacturing process audit** **9.2.2.4 Product audit** 9.3 Management review 9.3.1 General **9.3.1.1 Management review—supplemental** 9.3.2 Management review inputs **9.3.2.1 Management review inputs—supplemental** 9.3.3 Management review outputs **9.3.3.1 Management review outputs—supplemental**
All clauses No. 10—IV. phase ACT	10 Improvement 10.1 General 10.2 Nonconformity and corrective action 10.2.1 10.2.2 **10.2.3 Problem solving** **10.2.4 Error-proofing** **10.2.5 Warranty MS** **10.2.6 Customer complaints and field failure test analysis** 10.3 Continual improvement **10.3.1 Continual improvement—supplemental**
	Annex A: Control Plan **A.1 Phases of the control plan** **(a) Prototype** **(b) Pre-launch** **(c) Production** **A.2 Elements of the control plan** **General data** **Product control** **Process control** **Methods** **Reaction plan**

Table 1. *Cont.*

Phase of PDCA Cycle	ISO 9001 (Base) and IATF 16949 (Extension/Supplemental)
	Annex B: Bibliography—supplemental automotive **Internal audit** **Nonconformity and corrective action** **Measurement system analysis** **Product approval** **Product design** **Product control** **QMS administration** **Risk analysis** **SW process assessment** **Statistical tools** **Supplier quality management** **Health and Safety**

[1] MSSs—Management Systems Standards. [2] QMS—Quality Management Systems.

3.1. Development of the Visualized Cluster of IATF 16949 Standard

The visualized cluster is seemingly complicated, but its dynamic behavior facilitates the user with a simple orientation. The cluster is based on the so-called degrees of separation. The number of degrees depends on the complexity of the document being processed; the IATF 16949 cluster we created has a total of seven degrees of separation. Each subsequent level of separation increases the information available to the user.

The following steps describe the process of cluster formation and the basic characteristics of each step.

The first step involves creation of a central node, from which other nodes connected by connectors are networked (node switching). The central node is called “IATF Standard 16949:2016 AQMS” and is marked as a blue rounded rectangle with a colored circle that expresses a “halo” effect, see Figure 1. The number of degrees of separation in the first step is 0.

The second step involves the creation of 13 new nodes, which contain the “Introduction” section and a dozen of main Clauses plus two Annexes, according to Table 1. The nodes correspond exactly to the structure of IATF 16949. The nodes forming the Clauses and Annexes are activated with the first degree of separation. They are shown as blue rounded rectangles networked with a central node. Networking is oriented outwards from the main node to 13 new points. Individual nodes are linked with the core node by using edges, or so-called connectors. They vary based on the depth of the structure separation and the type of the node.

The third visualization step activates 36 sub-clauses, according to Table 1, and networks them with the main 10 clauses. For these nodes, blue rounded rectangles are also used as a mean for display. The Annexes also have their two Sub-annexes marked as “A1”. “Phases of the control plan” and “A2. Elements of the control plan”. Networking of PDCA clauses and sub-clauses also occurs in this step. Again, we use Table 1. The nodes for “Plan”, “Do”, “Control”, and “Act” are displayed as orange rounded rectangles with a round halo effect and a label expressing the rainbow cycle. Undirected connectors are visualized by a thick orange line. A very important node called “Alignment with ISO 9001:2015” with its connectors was also visualized. This is shown as a distinct green (reflective green) rounded rectangle. This node and its connectors are connected to all nodes (clauses, sub-clauses, etc.) that contain parts of the basic standard ISO 9001:2015. The last node marked as “ISO 9001:2015 QMS—Fundamentals and Vocabulary”, linked to Clauses 2 and 3, expresses the shared references, terms, and definitions for IATF 16949 of ISO 9001:2015. It is shown as a gray rounded rectangle with a small eye tag, see Figure 2, with a separation degree equal to two.

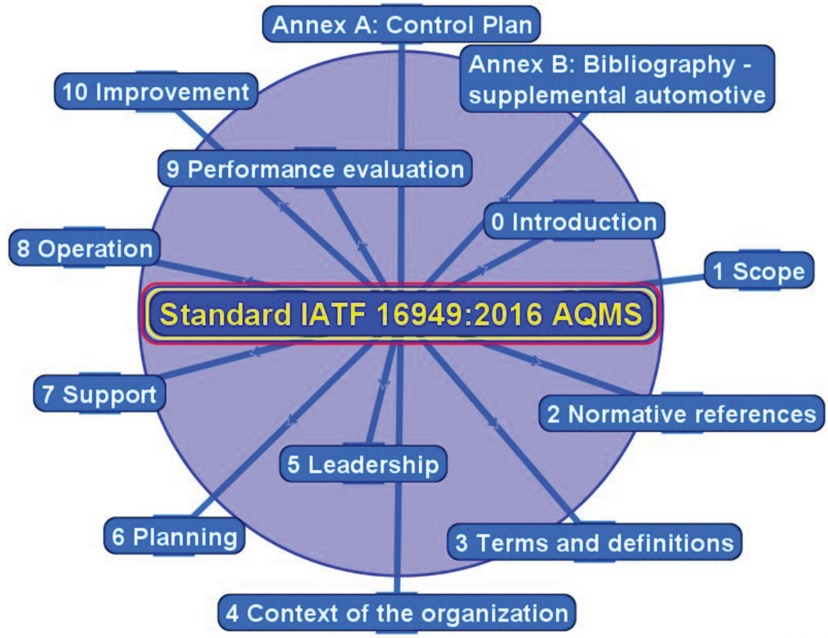

Figure 1. The core node "Standard IATF 16949:2016 AQMS" with its main clauses (Source: author).

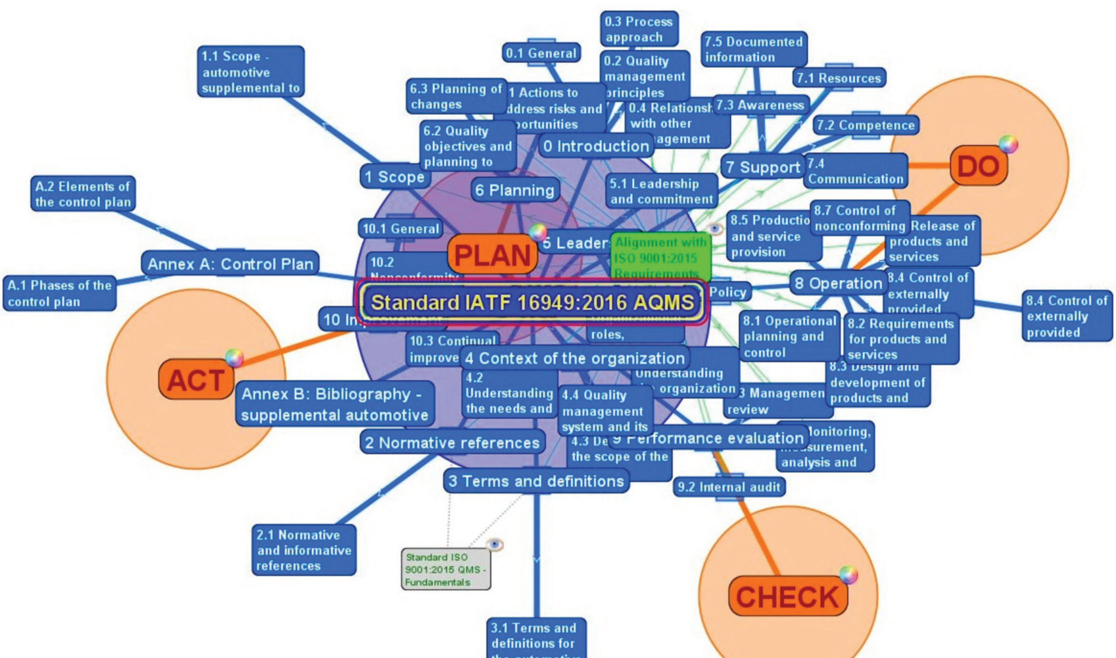

Figure 2. PDCA cycle cluster—nodes PLAN, DO, CHECK, ACT with their relations—software cut-out (Source: author).

The fourth step is a separation level equal to three, see Figure 3. It visualizes the sub-sub-clauses, in this case from the sub-sub-clause "0.3.1 General" to the sub-sub-clause "10.3.1 Continual improvement—supplemental" as blue rounded rectangles. These nodes are extremely important because they are related to the mandatory management system requirements according to the standard. The requirements of subclauses are shown in a distinctive red color with a circular halo effect in the background. To emphasize them, each requirement is assigned a label in the form of an icon. In our case, the anchor was chosen. Each node also has a number of requirements. Each requirement node is networked with the relevant clauses or subclauses that contain the requirement in the text of the standard. The connectors are solid, oriented lines in red color and connect individual nodes.

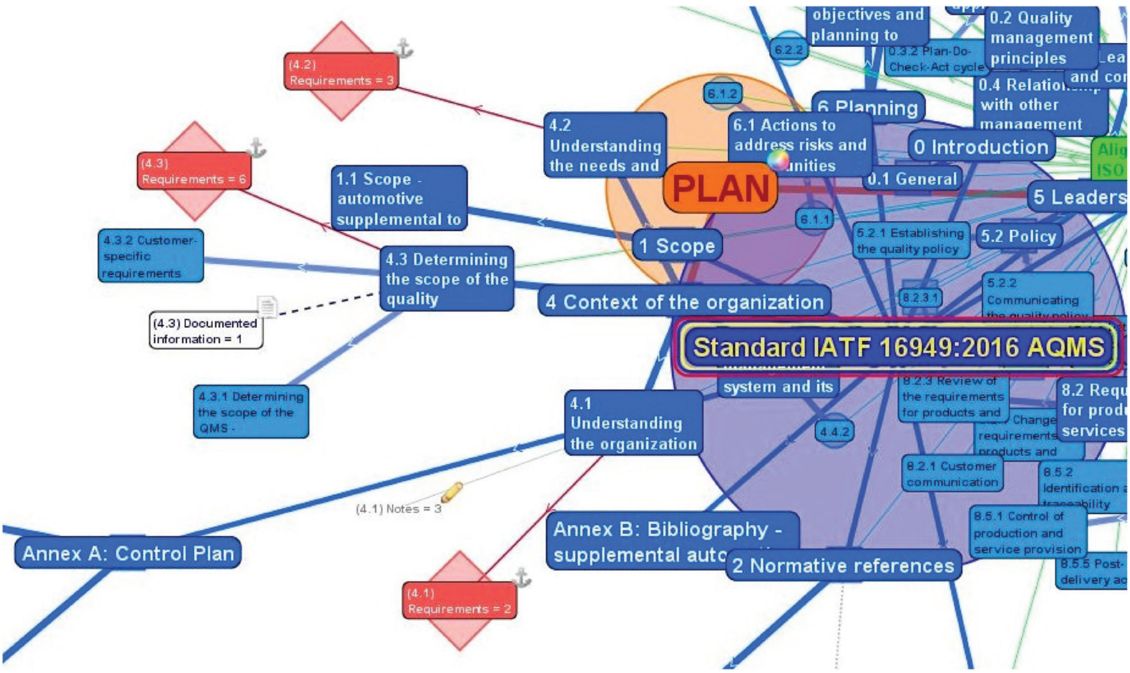

Figure 3. The cut-out of IATF 16949 cluster as viewed in the software with its affiliated requirements, documented information, and notes; (Source: author).

In the fourth step, the nodes for binding *Documented information* are also activated, because in addition to meeting the requirement, evidence must also be provided to the interested parties that the requirement was, in fact, met. Nodes for binding requirements are displayed as white rounded rectangles with a tag that represents the edited page of the document. In a similar way to requirements, the extent of binding documented information is provided. The connectors are expressed in a dark blue and unoriented, dashed line.

The nodes for *Notes*, which are listed for each clause or subclause, are also presented. They are displayed as gray text with a pencil mark tag. These nodes serve more as a closer look at the request. They are not binding, they are explanatory. Connectors are expressed by a gray and undirected solid line.

As the degrees of separation are progressing, more requests, documented information, and notes are added along with other sub-sub-clauses. Sub-sub-sub-clauses are already distinguished by the turquoise color of the node. When specifying the number of requests and documented information, the numerical interval is sometimes given, e.g., from—to. This is especially the case if the customer has additional requirements of the organization and requires documentation to prove the facts.

Together, the IATF 16949 cluster has seven degrees of separation, with more elements of this vast structure being displayed in turn. The complex model is shown in Figure 4. Due to the complexity of the figure, the same picture, but in its highest possible definition, was added to the section Supplementary Materials under the title: "Complex cluster for individual MSS according to IATF 16949".

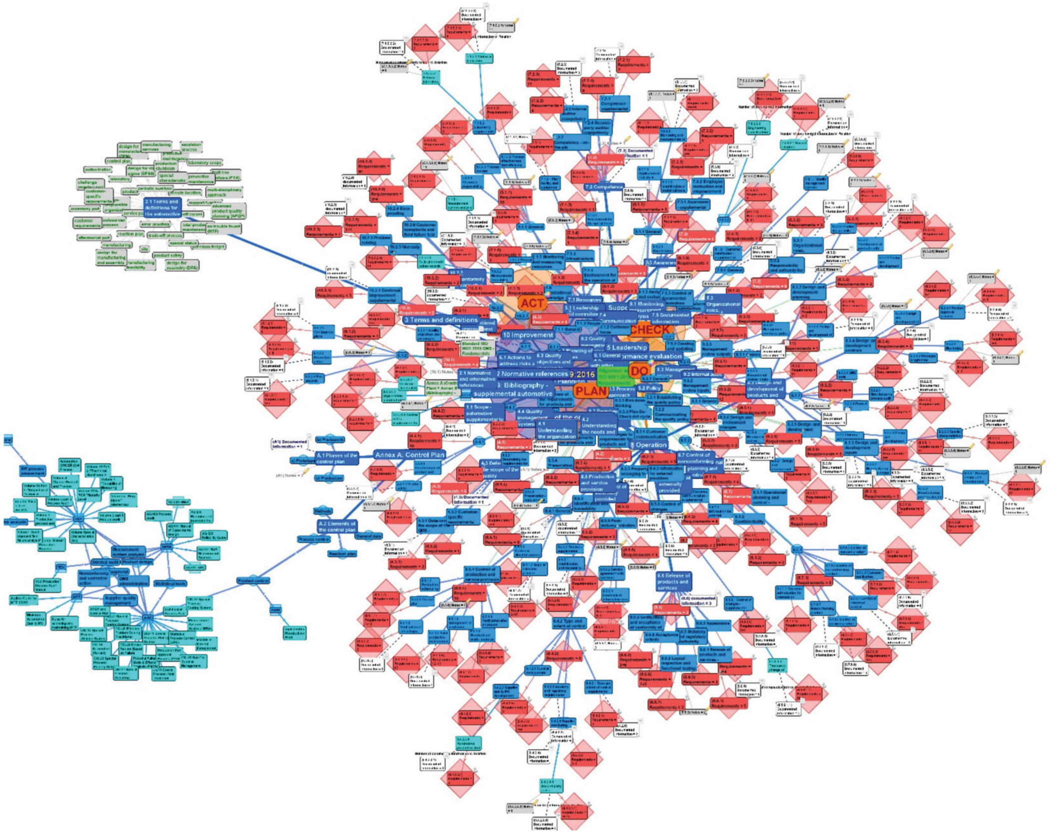

Figure 4. Full view of a complex cluster for individual MSS according to IATF 16949 —three with their affiliated clauses, subclauses, requirements, documented information, and notes; (Source: author). Note: Figure 4 is also available in the section Supplementary Materials in higher resolution.

It might seem that the model is becoming very confusing. In static display, this statement is true, but for dynamic display, it is possible to zoom the cluster, and create longer or even shorter connectors. Simply put, the user can jump directly to the part he needs to explore. It is also possible to activate a specific node or hide unnecessary nodes. The unique option is to "shake" the whole structure or just parts of it.

3.2. Management Review and Audits Support

In assessing the extent of cluster structuring, this visualization is the most extensive for one management system according to the standard because, as mentioned above, it connects two management systems into one. This system connection can be referred to as "internal integration". Managers must study two documents: ISO 9001 and IATF 16949. This visualized dynamic cluster serves as a tool, which allows the interested parties the so-called intelligent (smart) view and subsequent analysis and synthesis of management systems according to these two standards.

It follows that this is a valuable support for those stakeholders who must create, maintain, and continually improve the management system according to IATF 16949 in their organization. These are mainly the internal managers of the organization and internal auditors. For all parties involved in other party audits and certification audits, it is an excellent tool for minimizing discrepancies and nonconformities. The aim is, therefore, that the audits in the organization are carried out without the complications that arise when a standard-related audit criterion is not met.

The interested party can easily and quickly find out how many requirements to deal with and gain an insight into the text content of the standard by activating the given node (as a representative of the clause). Because the text of IATF 16949 is commercially provided this sharing must be limited to only examples in this article. Specifically, we chose and activated for selected visualized image (red-yellow border of the blue round rectangle) sub-sub-clause 8.6.3 "Appearance items", which lists the quality attributes for the appearance of the product, see Figure 5. The figure shows the text content of the activated node, located in the right part of Figure 5. This text corresponds precisely to the content of the sub-sub-clause No. 8.6.3 defined by the standard IATF 16949.

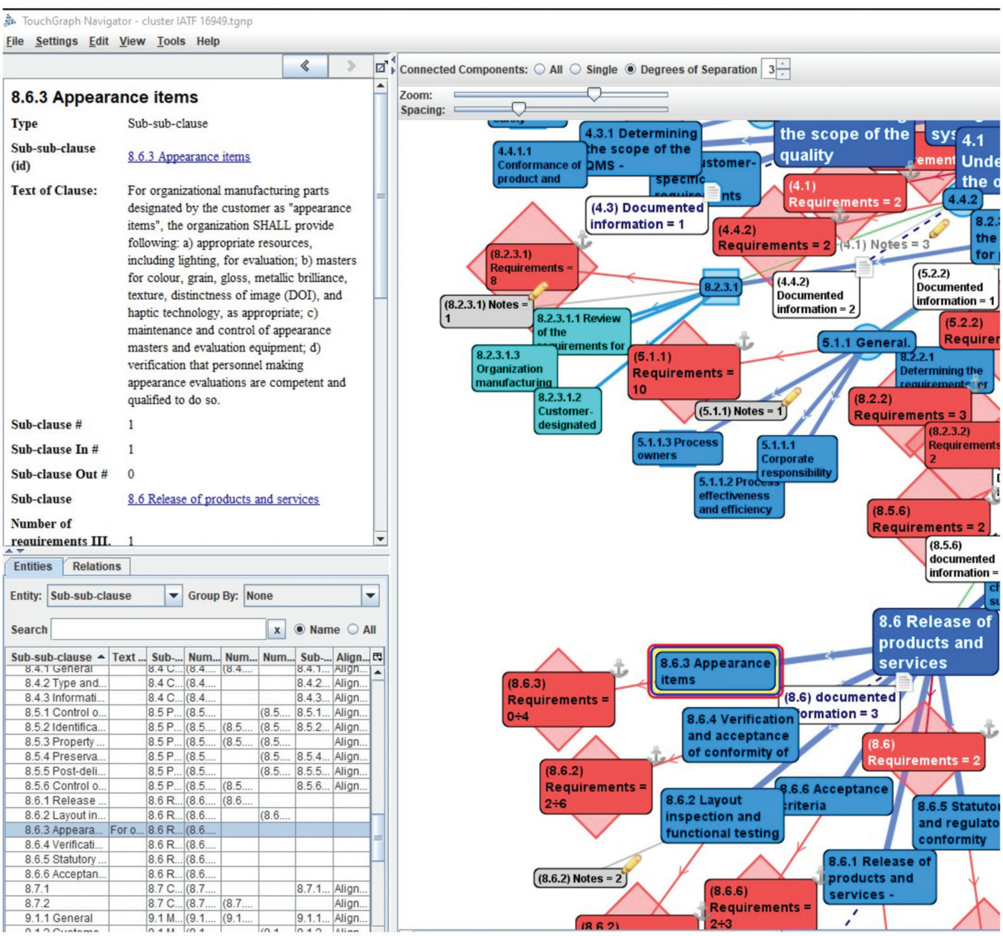

Figure 5. Partial display of the description window of the activated by sub-sub-clause 8.6.3 "Appearance items" for quick insight into the details of the given requirements (Source: author).

The advantage of this IATF 16949 visualization cluster is that it is possible to examine each item (clause, sub-clause, requirement, or documented information) separately. The given cluster also visualizes the connection with the ISO 9001 standard, i.e., it also makes the internal integration of the given management system available to interested parties. If the addition of other management systems according to ISO standards continues, the database in MS Excel could be expanded with new sheets, i.e., new management systems. This is especially advantageous for integration with consolidated management systems or those that have been revised [26].

4. Discussion

In organizations that manufacture products or provide services as well as in academic practice, the visualization of management systems standards is presented primarily in the form of static diagrams or tables. This article presents a visualization of the standard *IATF 16949 Automotive Quality Management System Standard, Quality management system requirements for automotive production and relevant service parts organizations*, which incorporates in its content *ISO 9001 Quality Management Systems—Requirements* using a dynamic cluster model built using software TouchGraph Navigator and MS Excel applications to create a source database.

This article is intended to highlight the usefulness of such an approach to technical specifications or standards for stakeholders who wish to plan, implement, maintain, and continuously improve the management system. These stakeholders include, in particular, the top managers of the organization, internal auditors, external auditors, but also auditees [27].

The presented cluster enables the analysis of the standard structure, its individual clauses, sub^{2}clauses, sub^{3}clauses, sub^{4}clauses, sub^{5}clauses (up until the fifth level), binding requirements and documented information and explanatory notes. In the cluster, after the activation of individual nodes, it is possible to display the text content of the standard and learn the specifications related to the requirements and documented information, which are required during the activities with the management system.

After the analysis, it is possible to develop an effective synthesis from the acquired knowledge and thus simplify and speed up the "manipulation" with the standard.

The article emphasizes the use of visual management for management systems of given standards, which could be perceived as management for management.

For further processing, it is possible to connect other management systems to the given cluster according to selected ISO standards and create twins, triplets, etc. Management systems, in Table 2, that have great potential for integrated visualization with respect to QMS and AQMS include the following management systems with HS or HLS structure.

From the research perspective it would be fitting to observe if the frequency of updates for ISO 90001, which is now set for five years, would be also suitable for the IATF 16494 due to the acceleration of the update in the form of Sanctioned Interpretation (SIs) of the Technical Specification for IATF 16949.

Furthermore, for the purpose of this research we intend to study if visualization, as a working tool, would enhance and simplify the understanding of the management systems and standards related to them. It will be useful to identify such visualization expressions that would have the support and acceptance of most stakeholders.

Finally, it will be appropriate to examine, considering that management systems according to ISO standards are restructured after updating and have an HLS or HS structure, whether there is a finite number of management systems that can be integrated into one organization while maintaining the functionality of the integrated complex.

Table 2. The selected ISO standards with a potential for integration visualization (arranged by standard number from lowest to highest).

Number of ISO Standard	Year of Publication	Title of Standard for Management Systems (MSs)	Requirements {R} Guidance for Use {G}	Reference
10012	2003	Measurement MSs	{R} for measurement processes and measuring equipment	[28]
14001	2015	Environmental MSs	{R} with {G}	[29]
27001 [1]	2013	Information technology—Security techniques—Information security MSs	{R}	[30]
22301	2019	Security and resilience—Business continuity MSs	{R}	[31]
28000	2007	Specification for security MSs for the supply chain		[32]
28001	2007	Security MSs for the supply chain—Best practices for implementing supply chain security, assessments and plans	{R} and guidance	[33]
28002	2011	Security MSs for the supply chain—Development of resilience in the supply chain	{R} with {G}	[34]
30301	2019	Information and documentation—MSs for records	{R}	[35]
37301	2021	Compliance MSs	{R} with {G}	[36]
39001	2012	Road traffic safety (RTS) MSs	{R} with {G}	[37]
44001	2017	Collaborative business relationship MSs	{R} and framework	[38]
50001	2018	Energy MSs	{R} with {G}	[39]
56001 [2]	202X	Innovation management—Innovation MSs	{R} with {G}	[40]

[1] ISO/IEC; [2] ISO/AWI.

5. Conclusions

One of the most widely used international standards for quality management in the automotive industry, ISO/TS 16949, is being developed with the release of a new global industry standard by the International Automobile Task Force (IATF). ISO/TS 16949 was initially created in 1999 by the IATF in cooperation with the ISO's Technical Committee on Quality Management and Quality Assurance (ISO/TC 176). It has subsequently become one of the most commonly used international standards in the automotive industry and it seeks to synchronize various assessment and certification systems in the global automotive supply chain.

IATF 16949:2016 was first published by the IATF in October 2016 and it supersedes and replaces the last version of the ISO/TS 16949. IATF 16949:2016 is in accordance with the latest version of the ISO 9001:2015 quality management system standard, refers to it, and entirely respects its structure and requirements. IATF 16949: 2016 is not an independent quality management standard but is implemented in addition to and in conjunction with ISO 9001:2015. The IATF will ensure continual conformity to the ISO 9001 by maintaining strong cooperation with ISO through its participation in ISO/TC 176 [41].

The aim of the article was to present a visualization cluster that supports this conjunction and helps decision-makers as well as other stakeholders. It also intends to support persons involved in the preparation of the implementation of several standards within the organization. Implementing a standard cluster that incorporates IATF 16949, ISO 9001, and ISO 9000 standards can lead to effective preparation for certification, which is considered an indicator of success where the organization demonstrates its commitment to systemic management. Such an approach can inspire organizations to expand their internal operational processes by integrating sustainability and quality aspects into their operational contexts. As stated by Silva et al. [42], QMS aims to help organizations respond to change by creating more open and agile models. The QMS also aims to promote ongoing dialogue with stakeholders, to respond more flexibly to current challenges and to create a lasting systemic environment. The effectiveness of such an approach is reflected in the increased adaptability of production and in the shortening of the reaction time to the implementation of changes. The result is reflected in the greater competitiveness of the organization.

The benefits of the application of visualization in practice are both internal and external. The internal benefits include, for example, raising the awareness of top management and internal stakeholders about the implementation of IATF 16949 in automotive organizations, and its use as a powerful decision-making tool. Visualization offers an insight into complexity and a scope of the management system according to IATF 16949 and better understanding of the internal integration between ISO 9001 and IATF 16949 as an inseparable pair of management systems.

Flexibility is yet another benefit to visualization because the organization can eventually add other management systems to the picture and adjust existing clusters according to its changed requirements.

Reducing administrative requirements is also considered as a benefit, as visualization contains a significant amount of supporting documentation that does not have to be stored physically.

From an external point of view, we can consider the advantage of increasing the competitiveness of the organization by obtaining quality certification [43]. The visualized format of the standard is very helpful during the audit. Information found in the clauses "Management review" and "Improvement" are especially important during the process and simplified access to this information can streamline the process of certification or re-certification.

Limitations of the software application are mostly seen during the creation of a certain number of nodes and edges; the number depends on the type of SW and its quality. Moreover, at low resolution, the 2D views of nodes and description may be unreadable. The study of IATF 16949 is limited to a comprehensive 3D view.

The ultimate goal of every manufacturer or service provider in the automotive industry is to offer high quality products and services, to be successful and competitive, and at the same time to be able to meet all the necessary requirements for sustainable production or service provision.

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Data Availability Statement: The first part of data supporting reported results in this research can be found on the web pages of the International Automotive Task Force. These links are publicly archived: https://www.iatfglobaloversight.org/wp/wp-content/uploads/2021/07/IATF-16949-SIs-July-2021.pdf (accessed on 3 December 2021); https://www.iatfglobaloversight.org/wp/wp-content/uploads/2021/03/IATF-Rules-5th-Edition_FAQs-February-2021.pdf (accessed on 3 December 2021). The second part of data supporting reported results in this research can be found on the web pages of the International Standard Organization. These links are publicly archived: https://www.iso.org/obp/ui/#iso:std:iso:9001:ed-5:v1:en (accessed on 3 December 2021); https://www.iso.org/obp/ui/#iso:std:iso:9000:ed-4:v1:en (accessed on 3 December 2021).

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Partial Order as Decision Support between Statistics and Multicriteria Decision Analyses

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Abstract: Evaluation by ranking/rating of data based on a multitude of indicators typically calls for multi-criteria decision analyses (MCDA) methods. MCDA methods often, in addition to indicator values, require further information, typically subjective. This paper presents a partial-order methodology as an alternative to analyze multi-indicator systems (MIS) based on indicator values that are simultaneously included in the analyses. A non-technical introduction of main concepts of partial order is given, along with a discussion of the location of partial order between statistics and MCDA. The paper visualizes examples of a 'simple' partial ordering of a series of chemicals to explain, in this case, unexpected behavior. Further, a generalized method to deal with qualitative inputs of stakeholders/decision makers is suggested, as well as how to disclose peculiar elements/outliers. The paper finishes by introducing formal concept analysis (FCA), which is a variety of partial ordering that allows exploration and thus the generation of implications between the indicators. In the conclusion and outlook section, take-home comments as well as pros and cons in relation to partial ordering are discussed.

Keywords: partial order; MCDA; ranking; rating; evaluation; indicators; generalized linear aggregation; peculiar elements; formal concept analysis

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1. Introduction

A variety of methods for multi-criteria decision analyses (MCDA) exist [1], such as the ELECTRE family [2–4], different variants of PROMETHEE [5] or AHP [6]—just to mention a few, typically applied for decision analyses and/or ranking or rating tasks. The present paper focuses on an alternative methodology, i.e., partial ordering [7]. Thus, the immediate question to be asked is, "Why should one add another method, such as partial ordering?" A possible answer could be that partial ordering applied to indicator systems is simple from a mathematical point of view (cf. the methodology section), but obviously that is not an adequate answer.

The question "Why Partial Order?" is not asked for the importance of the corresponding mathematical field. Partial Order is in its own right a relevant area of discrete mathematics, and the number of books as well as the appearance of its own journal indicates this [7,8] (cf. also the extensive reference list at the end of the paper). Thus, when the question "Why Partial Order?" is posed, then this question aims at the application of partial order theory in decision making and evaluation. The background mathematics are simple, although they may not be part of the traditional knowledge of scientists and of most MCDA because it has not the arithmetic point of view but the relational one as its focus. Thus, it appears appropriate to present simple examples, one taken from the area of sociology, the well-being of children and young people, as a subject for illustration of the abilities of partial ordering, plus an example from the field of toxic chemicals.

1.1. An Exemplary Case

In 2007, UNICEF reported [9] on the well-being of children and young people. The study covered twenty-one nations and applied six indicators (Table 1).

Table 1. Indicators of the UNICEF study concerning child well-being [1].

Indicator	Abbreviation	Remarks
Material well-being	wb	Related to poverty, household equipment
Health and Safety	hs	Immunization, mortality
Educational well-being		Achievements
Family and peer relationships	fa	Family structure
Behavior and risks	br	Experience of violence
Subjective well-being	sub	Personal well-being

[1] For detailed information of this study cf. [7,9].

The overall objective of the study was the ranking of the twenty-one nations, and for that purpose, the final step was an aggregation of the six indicators to a composite indicator ci by summing the indicator values found for each nation:

$$ci(x) = \sum g(j) \cdot q(j) \tag{1}$$

with g(j) as the weight of the jth indicator, i.e., wb, hs, . . . , sub. The label "x" indicates one of the twenty-one nations. In the original study, all weights were selected to be "1", i.e., the six indicators (Table 1) contribute to ci1 with the same weight, namely "1".

For this exemplary didactic demonstration, three indicators, i.e., wb, hs and br, and arbitrarily eight nations, Sweden (SWE), Denmark (DNK), Finland (FIN), Norway (NOR), Ireland (IRE), Germany (DEU), France (FRA) and the Czech Republic (CZE) were selected. To illustrate the effect of different weight regimes, besides the regime of weights applied by the scientists of the study [9], i.e., ci: g(wb) = 1, g(hs) = 1, g(br) = 1, two further regimes were introduced: ci2: g(wb) = 3, g(hs) = 2, g(br) = 1 and ci3: g(wb) = 1, g(hs) = 2, g(br) = 3, applying Equation (1). The data are taken from the UNICEF study; they are summarized in Table 2 together with the aggregated data applying Equation (1) for the three weight regimes for the three indicators: wb, hs and br.

Table 2. Data for the exemplary case.

	Original Data			Aggregated Data		
Nation	**wb**	**hs**	**br**	**ci1**	**ci2**	**ci3**
SWE	1	1	1	3	6	6
DNK	4	4	6	14	26	30
FIN	3	3	7	13	22	30
NOR	2	8	11	21	33	51
IRE	19	19	4	42	99	69
DEU	13	11	11	35	72	68
FRA	9	7	14	30	55	65
CZE	11	10	9	30	62	58

Based on the data given in Table 2, we can now rank the eight nations for each of the three weight regimes:

$$ci1: SWE < FIN < DNK < NOR < FRA = CZE < DEU < IRE \tag{2}$$

$$ci2: SWE < FIN < DNK < NOR < FRA < CZE < DEU < IRE \tag{3}$$

$$ci3: SWE < DNK = FIN < NOR < CZE < FRA < DEU < IRE \tag{4}$$

Looking at the ranking according to ci1 (Equation (2)), a nontrivial equivalence appears as FRA and CZE have the same ci1 value although they are clearly different countries! Thus, that FRA ≅ CZE means that there is equality of their ci1, only related to ci1.

It must be emphasized that the above-mentioned sequence expresses a $< -$relation without giving any indication whether the difference ci1(x)–ci1(y) may be large or small (in absolute terms). For example, FIN and DNK differ by one unit, whereas DNK and NOR differ by 7 units; nevertheless, FIN < DNK < NOR. The numerical point of view is only important to decide whether a $< -$relation can be established; all other metric details are ignored.

Turning to the ci2 regime (Equation (3)), where the weights are different from those of the UNICEF, the sequence changes. Thus, the equivalence FRA ≅ CZE is broken, but otherwise the relationships remain.

For the ci3 regime, again an equivalence (a tie) is noted; here DNK ≅ FIN, and further changes in the ordering are noted.

In the strict sense, only the sequence based on the ci2 regimes (Equation (3)) is a true ranking, since no equivalences (no ties) are found, whereas the two other sequences (Equations (2) and (4)) are called weak orders and may be seen as ranking with ties. However, does this justify the ci2 weight regime, denoted shortly as (3,2,1), as a better choice than the ci1 regime (1,1,1)? In general, selection of weights may be highly subjective, albeit weights express experience of stakeholders at least in a qualitative way. Therefore, loss of knowledge related to each single indicator due to the aggregation to a (one-dimensional) composite indicator, the knowledge of stakeholders, should not be ignored. However, the method to integrate this mathematically is the challenge.

Further, it can be seen that any of the three original indicators, wb, hs and br, may introduce their own, possible weak and different orders that can immediately be seen (Equations (5)–(7)).

$$\text{wb:} \quad \text{SWE} < \text{NOR} < \text{FIN} < \text{DNK} < \text{FRA} < \text{CZE} < \text{DEU} < \text{IRE} \tag{5}$$

$$\text{hs:} \quad \text{SWE} < \text{FIN} < \text{DNK} < \text{FRA} < \text{NOR} < \text{CZE} < \text{DEU} < \text{IRE} \tag{6}$$

$$\text{br:} \quad \text{SWE} < \text{IRE} < \text{DNK} < \text{FIN} < \text{CZE} < \text{NOR} = \text{DEU} < \text{FRA} \tag{7}$$

It is immediately noted that the positions of the nations change depending on the selection of indicators. Hence, the question arises: Which < -relations are common for all three indicators? This question brings the theory of partial order into play. To disclose what is common considering all (in the example, three) indicators simultaneously, there are two methods. One is to simply investigate the intersection of three sets of ordered pairs (see below) and may be called the set theoretical method; the other is to check the numerical values (see methods section) and may be denoted as the value-oriented method. The two methods are equivalent. Here, the first one, the set theoretic method, will be applied to continue with the logic of this section.

In order to construct the set of ordered pairs, the notation (a, b) is used to express a < b, where "a" and "b" stand for the objects under consideration, here the nations. For wb, the set of ordered pairs is

{(SWE, NOR), (SWE, FIN), (SWE, DNK), . . . ,(FIN,DNK), . . . (NOR, FIN), (NOR, DNK), (NOR,FRA), . . . ,(DEU,IRE)}.

For the indicator hs, it is found, besides others, {(SWE,NOR), . . . , (FIN,NOR), . . . }.

In common for wb and hs would be (SWE,NOR), but neither (FIN,NOR) nor (NOR,FIN), as due to wb: NOR < FIN, but due to hs: FIN < NOR. It is obviously a troublesome procedure to check all sets of ordered pairs manually (the number of sets equals the number of indicators—here three). Hence, a software package, "PyHasse", was developed to disclose which relationships are in common for all three indicators (for details, see Section 4). The result of this exercise is shown in Figure 1.

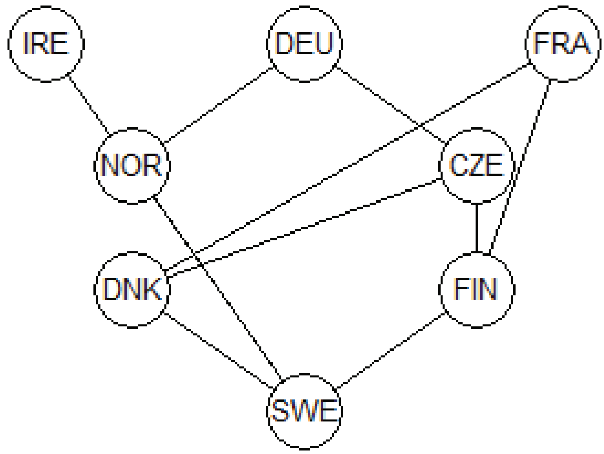


Figure 1. Graphical representation of the partial order of the above exemplary case.

This diagram in Figure 1 is known as a Hasse diagram. The diagram has 15 comparisons and 13 incomparisons and expresses that for nations linked by line-segments either only upwards or (exclusively) downwards, such as, e.g., SWE, FIN, DEU and CZE, a sequence, namely SWE < FIN < CZE < DEU can be stated, even when

- a simultaneous consideration of all three indicators is performed, i.e., independent of the specific indicator, and
- no aggregation to form a composite indicator is applied, and hence no weights are necessary.

Further, SWE < DNK < FRA can simultaneously be ordered by all three indicators. In other words: the indicator values along such sequences are co-monotone, i.e., if the value of one indicator increases, the other indicators increase as well or remain constant. In the terminology of partial order, objects (here the nations) that are connected by a line segment or a sequence of line segments (either up or down) are called comparable. Decision analysis aims at finding all objects under consideration as comparable, because then there will be a best, second best, etc., and a worst object (here nation).

Looking at Figure 1, the next question could be: What about IRE and, e.g., NOR? Considering the sequences (Equation (5a)–(5c)), IRE changes its position from the best (wb and hs) to a low position (5c). Whereas many nations are mutually comparable, IRE is incomparable with NOR, as for two indicators (wb and hs) IRE has high values whereas for one indicator, namely br, a low value. In contrast, NOR has a low value in wb, a medium value in hs and a value better than IRE in br. Thus, there is a conflict. IRE is good in two indicators, but bad in one, whereas NOR is worse than IRE in wb and hs, but remarkably better in br.

The key point is that when only one of the sequences (Equations (2)–(4)) is considered, this conflict is not visible. A decision maker may decide that IRE does not need any management, because it is anyway in a particularly good state despite a low ranking in br (cf. original data in Table 2).

A First (Preliminary) Conclusion

Partial order can be useful when multi-indicator systems are the basis for a decision (in contrast to methods based on probabilities) because it shows where indicator values are expressing a conflict, which, once identified, may cause appropriate management. Along with other scientists working with partial order, Roy and Vanderpooten [10], with their reflection about decision support systems, and Fishburn [11,12], who relates utility functions with partial order constructs, such as linear extensions, should be mentioned.

2. An Attempt for a Positioning of Partial Order

First, it should be mentioned that both ELECTRE [5] and PROMETHEE [2–4] use partial order methodology as an interim step. However, these methods apply further steps. Thus, partial order aspects do not play an essential role. On the other hand, other methods such as AHP [6] or TODIM [13] ignore at the very beginning partial order concepts. This intensifies the question, posed in the introduction: Why?

When the aim of MCDA is to provide a ranking to provide optimal and suboptimal options (in case of external constraints) for use in decision making, the concept of ranking is typically required to deliver a unique order among the options or objects. Hence, the resulting order should have neither several nontrivial equivalence classes (i.e., objects that have the same final ranking index without being identical (see Table 2, the composite indicator values ci1 for CZE and FRA)) nor, possibly more importantly, incomparabilities, i.e., objects that have some indicator(s) favorable in comparison to other objects, but other indicator(s) disadvantageous, at least in terms of ranking (see, for instance, NOR and IRE in Figure 1).

The typical result of a partial order is, unfortunately, to have incomparabilities. Thus, MCDMs must go beyond partial order to provide a ranking. There are three counterarguments that put partial order more into the foreground:

1. The objective of any MCDA method is a ranking construct (by different and often highly sophisticated techniques) requiring a ranking index, which is a scalar as only a scalar can assure the absence of incomparabilities. Nevertheless, a scalar does not necessarily prevent the presence of nontrivial equivalence classes, and even if the unwanted effect of incomparabilities is avoided, the construction of a scalar from indicator values must take care to reduce as much as possible the ties with respect to the values of the scalar. However, the main point of construction of a scalar is the fact that incomparabilities are suppressed, although such incomparabilities indicate severe conflicts among the options or objects; disclosure of these conflicts should not be ignored.
2. Any aggregation, mapping m indicators onto a one-dimensional scalar, such as one of the ci's above, ignores specific information of the single indicators. In the final sequence, in ci1 it is no more evident that IRE is good with respect to wb and hs but strikingly bad with respect to br, which should evoke specific management plans. IRE is independent of the weight regime at the top of the sequences (2)–(4).
3. The construction of a scalar is necessarily a mapping of a multidimensional system onto a one-dimensional quantity. Then, depending on the technical form of construction, compensation effects may develop [Munda, 2008], i.e., favorable indicator values may compensate for unfavorable ones. Accepting that partial order can deliver incomparabilities also means that in such cases compensation is conceptually eliminated; furthermore, conflicts are brought into the light. In light of the example above: IRE needs no management because IRE is at the top of sequence (2) (and the other two). Nevertheless, IRE has a deficit in br. This deficit is balanced out (compensated for) by the two good values in wb and hs.

2.1. Partial Order in Its Application on Multi-Indicator Systems (MIS)—An Attempt for a Localization within the Context of Other Mathematical Disciplines

The theory of partial order is relatively young and was invented with a pure algebraic/numeric theoretical approach at the end of 19th century [14–16]. At that time, partial order was as a theory of relations, an algebraic topic settled between graph theory, algebra and combinatorics. By the work of Garret Birkhoff [17] and Helmut Hasse [18], partial order received broader attention; however, it still remained a special topic in the field of pure mathematics. With the pioneering paper of Halfon and Reggiani [19], partial order entered the field of decision support, and hence, the question arises over how to localize partial order within operations research with MCDA as a special field, and with statistics, both traditionally disciplines in data analysis and decision support. Here may be the right place to check partial order with respect to three pillars of statistics:

Three Pillars of Statistics and the Partial Order Counterpart

Statistics can be seen as consisting of three pillars:

1. *Descriptive statistics* Partial order (in its application to MIS) is based on standard statistics and does not add (at least up to now) its own concepts.
2. *Explorative statistics* Partial order can explore data as to how much they contribute to a ranking. The background is its graph theoretical basis, which consequently leads to the question of why the graph induced by partial order has certain structures.
3. *Inference statistics* Inference methods aim at a decision as to how far results from certain random sampling or spot tests can be extended to a universe. This important question should also be transferred to partial order applications. However, there the focus is on the objects for which a decision is to be found, and not on the generalization. Nevertheless, first attempts to judge the role of noise within partial order can be found in [20]. At least it cannot be claimed that a test theory in partial order applications is at hand.

In relation to exploration of the eminent, important branch of partial order, the theory of Formal Concept Analysis (FCA), founded in the 1980s by the group of H. Wille [21–23], must be mentioned. The basis for an analysis by FCA is the lattice theory, which can be considered as partial order additionally equipped with certain axioms. Each lattice is a partial order, but each partial order cannot be considered an outcome of lattice theory. So powerful is FCA, and so restrictive are the additional requirements on data, that FCA is not generally applicable. Recently, Kerber and Bruggemann [24] developed concepts to generalize FCA to continuous data. However, data statistics offers powerful methods for continuous data in concept, and it seems clear that an exploration will first apply well-known concepts of explorative statistics before the theoretically challenging methods of Kerber et al.

3. Basic Concepts of Partial Order in Application on MIS

3.1. Basic Equation

Whereas the mathematics of partial order can be overly complex, because graph theory, algebra and combinatorics are intertwingled, the mathematics of partial order applied on MIS is simple. Here is not the place for a formal introduction because there are several textbooks and many publications available (cf., e.g., [7]. Nevertheless, it is convenient to have some basics and some notations at hand. Most important is the basic equation of the value-based method to create a partial order:

- Objects: the items for which a decision is to be found, i.e., for which a ranking is the objective.
- Indicators: as most often the ranking objective, for example urban quality, cannot be directly measured, a set of indicators is defined that describe the important aspects of the wanted ranking. As several indicators are needed (as in the example above six indicators for child well-being), a multi-indicator system (MIS) is consequently found.

Let q(j,x) be the jth indicator of a MIS with a value for the object x. Then a $< -$relation between objects x and y is found when the following definition is fulfilled:

$$x \leq y\text{: if and only if } q(j,x) \leq q(j,y) \text{ for all j, i.e., for all the indicators of a MIS.} \quad (8)$$

If q(j,x) = q(j,y) for all j, then objects x and y are equivalent, $x \cong y$ (with respect to the MIS).

If for some indicators q(j,x) < q(j,y) and for others q(j,x) > q(j,y) then objects x and y are mutually incomparable. Obviously by some indicators x is to be preferred, whereas for some other indicators y is to be preferred (the conflict situation). Clearly Equation (8) can also be applied to any single indicator. Thus, x and y may either be equivalent or x < y or x > y. One of these three possible cases will always prevail; hence, for a single indicator, always a set can be found, made of the pairs (x,y) with x < y (here the appearance of equivalences is suppressed in order to focus on the main logic). Hence, the set theoretical method is based on the value-based method taken for each single indicator.

3.2. Important Notations

Some notations simplify communication about results of partial order within the context of a MIS:

- Maximal element: If there is no y for which y > x is valid, then x is called a maximal element.
- Minimal element: If there is no y for which y < x is valid, then x is called a minimal element.
- If there is only one maximal (minimal) element, then this element is called a greatest (least) element.
- If x is at the same time a maximal and a minimal element, it is called an isolated element (from an explorative point of view, isolated elements indicate interesting data structures).
- Let X be the set of all objects of a study. Then X′ as a subset of X is called a chain if for every element of X′ it is found x < y or x > y.
- X″ is a subset of X called an antichain if for any two objects taken from X″ an incomparability is found.

With Figure 1 at hand, we can exemplify these few notation items:

- IRE, DEU and FRA are maximal elements
- SWE is a minimal element: it is a least element because it is the only nation that is a minimal element.
- {SWE, DNK, DE, CZE} is an example of a chain. Indeed, it is found: SWE < DNK < CZE < DE
- {NOR, CZE, FRA} is one example of an antichain. Indeed, Equation (6) cannot be applied for any pair of objects taken from this subset.

It is particularly important to understand that classification of objects into chains or antichains or into the set of maximal or minimal elements is always to be seen as the background of the actually used MIS.

3.3. Generalized Linear Aggregation

As stated above, the knowledge of stakeholders, even though often arbitrary and subjective, is a part of experience that should not be ignored. The problem is the qualitative nature of weights, which induces in decision-making processes long and often controversial debates. As shown in the example of child well-being, a possible solution is to check alternatives for the weight values. Instead of only applying (1,1,1) as the weight regime, other weight regimes should be inspected to see how the final ranking is affected.

When a set of weights is written like a vectorial quantity (for example all weights are 1), then g1 = (1,1,1) (in the example) is applied to the matrix of indicator values. Written as a matrix equation:

$$(1,1,1)\begin{pmatrix} \mathrm{wb(x1)}, & \mathrm{wb(x2)}, & \ldots\ \mathrm{wb(xi)} \\ \mathrm{hs(x1)}, & \mathrm{hs(x2)}, & \ldots\ \mathrm{hs(xi)} \\ \mathrm{br(x1)}, & \mathrm{br(x2)}, & \ldots\ \mathrm{br(xi)} \end{pmatrix}$$

Performing matrix multiplication leads to a one-dimensional quantity, the ci1 (as already mentioned).

Similarly, other weight regimes can be applied in the same manner.

Finally, there will be as many composite indicators, ci, as weight regimes that can be meaningfully applied. This means that by matrix multiplication a new MIS is obtained that needs the same partial order tools as the original one. Then, there will once again be conflicts, but usually much fewer conflicts than in partial orders obtained from the original MIS. One may see this as the consequence of the additional knowledge beyond the pure data matrix. Instead of performing the matrix multiplication for each weight regime separately, one can also condense all the additional knowledge (by the weights) by writing:

$$\begin{bmatrix} 1,1,1 \\ 3,2,1 \\ 1,2,3 \end{bmatrix} \begin{bmatrix} wb(x1), wb(x2) \ldots wb(xi) \\ hs(x1), hx(x2) \ldots hs(xi) \\ br(x1), br(x2) \ldots br(xi) \end{bmatrix}$$

maintaining the example of child well-being (see introduction; here subscript i equals eight for the eight nations).

This way of summarizing all stakeholder knowledge means that a matrix equation plays the key role. With G, a matrix organized as follows: Rows: different possible weight regimes, Columns: the single weights for each indicator, and the original MIS as a data matrix, the general equation is:

$$G \cdot MIS(orig) = MIS(new) \quad (9)$$

Equation (9) does not only express in a clear and compact way the role of uncertainty with respect to the weights, but allows analysis of the role of weight regimes by statistical methods, now considering G as a data matrix in its own right. It should be noted that applying Equation (7) implies that the scaling level of the data of MIS(orig) allows such arithmetical operation. At least the data of the MIS(orig) must be carefully checked. Data ordinal in nature do not allow an operation such as Equation (9). When, nevertheless, Equation (7) is applied, then, for example, normalization of the data of MIS(orig) is a relevant step and must be at least explicitly mentioned. One should be aware that acting with ordinal data as if they are metric infers additional information into the dataset.

4. Software

Although the basis of partial order applied on MIS (Equation (6)) is conceptually quite simple, an analysis of m indicators and n objects becomes quickly tedious and error-prone. When n objects are present, then $m\ n\ (n-1)/2$ pairs must be checked to decide whether Equation (6) is fulfilled.

Therefore, the support of appropriate software is needed. The software applied here is PyHasse (Hasse diagrams based on program codes of Python). Today, PyHasse contains more than 140 modules, comprising a few very specialized and rarely applied ones and others that are main workhorses. Details can be found in [25,26].

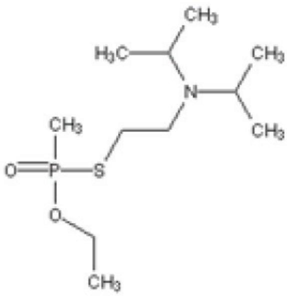
A new software package is under development and is available via the web. However, only a few modules are presently ready. It should be noted that other packages are recommended, for example PARSEC [27] and recently POSetR [28]. The original PyHasse software package is available from the second author.

5. Selected Examples of the Application of Partial Ordering

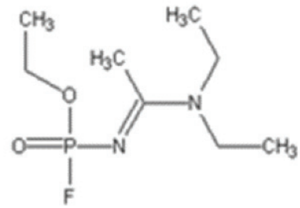
In the following, selected examples of the application of partial ordering for decision making and evaluation are described.

5.1. Novichok—Why the Skripals Did Not Die

On 4 March 2018, the former Russian spy Sergei Skripal and his daughter Yulia were poisoned in Salisbury by a nerve agent, later verified to be a member of the Novichok class, more precisely apparently A-234. Novichok (in Russian Новичок = newbie or newcomer) is the name of a group of compounds that are closely related to the well-known nerve agents VX (CAS 050782-69-9) and VR (CAS 159939-87-4). For further structures, [29] should be consulted.



VX



A-234

Fortunately, the Skripals did not die, which was somewhat surprising since A-234 was claimed to be even more toxic than the more well-known VX. Why did they not die? Several factors may come into play to explain this.

First, it should be mentioned that calculations determining the lethal concentration [29] have shown that A-234 is less toxic than VX (roughly by a factor of seven, which in this context probably is of minor importance. More important, it appears that factors such as skin penetration (J), evaporation (Evap), systemic absorption (Sys) and sorption in the outer layers of the skin (Cor) (Table 3) play a role, too. The main reason for this selection of factors is that apparently Novichok was administrated by contaminating the door handle of the Skripal residence, i.e., the transfer to the Skripals was through skin contact.

Table 3. Indicator values used for the Novichok study.

Compound #.	Name	J_{max}	Sys	Evap	Cor
1	VX	1.537	90.5	8.8	0.73
2	VR	1.149	61.2	38.3	0.57
3	A-230	0.424	15.1	84.8	0.10
4	A-232	0.255	13.2	86.7	0.12
5	A-234	0.345	17.8	82.1	0.16
6	Novichok-5	0.250	51.8	39.9	8.51
7	Novichok-7	0.187	45.6	39.5	15.35
8	'Iranian'	0.193	55.9	5.7	39.69
9	misc.	0.013	0.5	99.5	0.00

A simple partial ordering based on these four factors as indicators for the nine Novichoks (for structures, etc., see [29]) unfortunately leads to an HD with a rather low level of information (Figure 2).

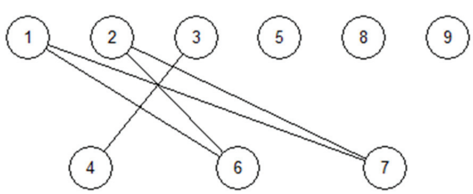


Figure 2. Hasse diagram of the nine nerve agents based on the four indicators given in Table 3.

Obviously, the diagram has a rather low level of information, with only 5 comparisons and 31 incomparisons. However, virtually all data applied originate from calculations [29]. Thus, they should be taken with some caution. The dominance of incomparabilities is a clear signal that the calculated values [29] alone would mask the role of other factors. Here, two separate methods have been applied, both available as special modules of the PyHasse software: (1) introducing weight regimes and (2) introducing indicator noise/uncertainty.

(1) Introducing weight regimes is a way to say that maybe all values are not absolutely correct, but that they may be handled by using weights, e.g., 0.9–1.0, for all indicators. Doing so, a perfect linear ranking of the nine compounds is developed (Figure 3A), clearly demonstrating Novichok A-234 is not an 'optimal choice'. Obviously, this can be explained by low skin penetration (J), higher evaporation (Evap) (handle concentration lower than expected), decreased systemic absorption (Sys) and increasing sorption to the outer parts of the skin (Cor) (in the palms).

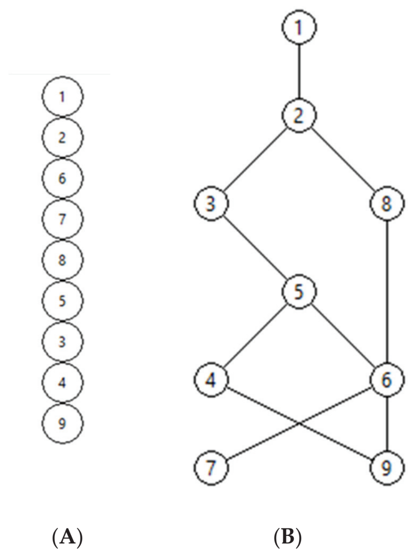


Figure 3. Hasse diagram of the nine nerve agents applying weight regimes (**A**) and data noise (**B**). Note: 9 is covered by 4 and 8 but not 6; 6 is covered by 5 and 8.

(2) A similar result is obtained by applying noise/uncertainty as—again—the data may not be absolutely specific. Introducing 5% uncertainty for the four indicator values leads—again—to a ranking leaving A-234 (5) significantly lower than VX (1) and the Russian analogue (2) (Figure 3B); the overall ranking appears to be 1 > 2 > 3 > 5 > 8 > 4 > 6 > 9 > 7.

Hence, partial ordering constitutes a nice tool for such studies, here contributing to rationalization of the survival of the Skripals based on simultaneously taking all relevant factors into account in addition to considering data uncertainty/noise.

Later, another British lady was unfortunately exposed to the same Novichok, which turned out to be fatal. She got the poison in a perfume flacon that was found in the neighborhood. She sprayed the 'perfume' on herself; Thus, higher concentrations and possible inhalation of the highly toxic A-234, possibly combined with a more fragile general state of health may be the explanation for her death.

5.2. Stakeholders/Decision Makers Influence

If possible, the direct partial ordering of a series of objects by simultaneous inclusion of a number of indicators is a typical type of analysis. However, in many cases the resulting ordering does not lead to a sound foundation for decisions—the above Hasse diagram (Figures 1 and 2) are examples of such a situation. However, despite the obvious problems with assigning weights to single indicators (cf. the above exemplary example), it may well be advantageous to bring stakeholders or decision makers into play in such situations.

Return to the example in the introduction with the eight nations and the three indicators: wb, hs and br. Let us assume that the three weight regimes are suggested by three stakeholders or decision makers. Thus, we now have the original MIS (Table 2 original data) and a weight matrix (Table 4).

Table 4. Weight matrix for three stakeholders/decision makers to evaluate child well-being.

SH/DM	wb	Sh	br
SH1 (UNICEF)	1	1	1
SH2	3	2	1
SH3	1	2	3

Applying generalized linear aggregation (see Section 3.3) whereby the two matrices, i.e., the original MIS (Table 2) and the weight matrix (Table 4), are multiplied leads to a new MIS where all weight regimes are simultaneously brought into play (Table 5).

Table 5. The new MIS based on the generalized aggregation method.

Nation	ci1	ci2	ci3
SWE	1.000	1.000	1.000
DNK	4.667	3.333	5.000
FIN	4.333	3.667	5.000
NOR	7.000	5.500	8.500
IRE	14.000	16.500	11.500
DEU	11.667	12.000	11.333
FRA	10.000	9.167	10.833
CZE	1.000	10.333	9.667

The resulting Hasse diagram visualized in Figure 4 displays a much higher level of information (with 23 comparisons and only 5 incomparisons) and thus a better background for decisions, both directly and indirectly, as every stakeholder/decision maker has made his/her footprint on the evaluation/ranking. FRA and CZE are, by this method, both ranked five (counted from the bottom), thus mimicking the weak order found applying the weight regime ci1 (cf. Equation (2)).

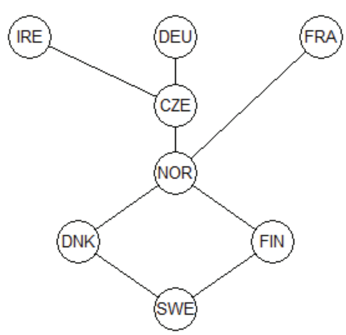


Figure 4. Hasse diagram applied after the application of operator G (Table 5) on the original MIS (Table 2).

5.3. Peculiar Elements/Outliers

Analyzing data, the question of peculiar element or outliers often arises. Partial order methodology offers an efficient method to disclose such elements [30].

When data are [0,1] normalized (for each indicator, checking all objects), then the geometric view of a successful ranking is an ellipsoid, ranging from (0,0, . . . ,0) to (1,1, . . . ,1). These two special points in the m-dimensional space are denoted as “ranking points”. Within the ellipsoid, certainly objects will be incomparable, i.e., deviate from the ideal line connecting the two ranking points. The question is as to how far the objects deviate from that ideal line, or, taking the opposite point of view, how near are objects to those corners of the m-dimensional cube $[0,1]^m$ (m indicators considered) that are not the ranking points. These corners are denoted as peculiar corners. Objects near the peculiar corners are called peculiar elements, and their data may be considered as interesting exceptions from the ideal line connecting the ranking points. The question is, when is a datapoint "near" the peculiar corners. Here a statistical point of view is taken, and a virtual m-dimensional ball is thought of, with one of the corners as center. The maximal Euclidean distance in an m-dimensional cube is $\sqrt{}$(m). Hence, a fraction of this maximal distance is an objective way to evaluate objects that are near a corner. This means it is not discussed but has a nearness based on a fraction of $\sqrt{}$(m). Most often the fraction is selected to be 0.05.

To illustrate the concept of peculiar elements/outliers, the 2017 data for gender equality within the European Union serve as an exemplary case [31]. The main indicators to elucidate gender equality according to Eurostat are summarized in Table 6 [31].

Table 6. Main indicators for disclosing gender equality.

Indicator	Short	Description	Orientation
sdg5_paygap	sdg5_pg	Unadjusted gender pay gap (% of gross male earnings)	Low better
sdg5_empgap	sdg5_eg	Gender employment gap (p.p.)	Low better
sdg5_caring	sdg5_car	Population inactive due to caring responsibilities (% of population aged 20 to 64)	Low better
sdg5_wparl	sdg5_wp	Seats held by women in national parliaments (%)	High better
sdg5_wmanage	sdg5_wsm	Positions held by women in senior management positions (%)	High better
sdg5_wsafe	sdg5_ws	Women who feel safe walking alone at night in the city or area where they live (%)	High better

Applying the partial order methodology, it was found that Finland is a peculiar element for the reason that the paygap for Finland is significantly lower than expected based on the indicator values for the 28 EU countries (note: prior to Brexit).

5.4. Formal Concept Analyses

A demonstration of Formal Concept Analysis (FCA) is difficult, because here a complete understanding would need to dive into depths of mathematics, especially in the theory of lattices, which are a special variant of partial order. Formal concept analysis combines both evaluation and—to some extent—exploration. The sections above already show the evaluative side of partial order, as any Hasse diagram visualizes the multitude of comparisons under the indicators, describing a ranking objective. Thus, demonstration of the exploration part remains.

The main reason behind binarization is that a certain element "possesses" the property q(j) if the value of qbin(j,x) = 1. The transformation equation can certainly be discussed because other variants are possible. However, the machinery of FCA is in focus here rather than a discussion of the details of the data (as, e.g., the statistical robustness or whether it fails to transform data in only a two-valued indicator).

At the heart of the exploration of FCA is the generation of implications. Consider the data given in Table 7.

Table 7. A fictitious example.

Objects	Two Binary Indicators Case A		Two Binary Indicators, Case B	
	q1bin	**q2bin**	**q1bin**	**q2bin**
a	1	1	1	0
b	0	1	0	1
c	0	0	0	0
d	1	1	1	1

In case A, it can be stated: if q1bin is a property of an object (such as for a and d, then q2bi is a property of the corresponding objects, too. In other words: q1bin implies q2bin (in case A, which is denoted as q1bin ⇒ q2bin). The reverse statement is not correct, because not all "1" of q2bin have a 1 as their counterpart in q1bin. In case B, q1bin does not imply q2bin, because q2bin(a) = 0 although q1bin(a) = 1.

Table 7 may be extended so that several indicators imply a subset of several others. Although this generalization sounds easy, it is in practice not an easy task to check a binary data matrix of, say, m indicators for implications of subsets of indicators. As 2^m subsets of indicators are possible, every set of 2^m subsets must be compared with every 2^m subsets taken from the set of m indicators. This comparison is to be performed over all objects; hence, the identification of implications is computationally challenging. There is an elegant solution of this problem by means of lattice theory; however, an explanation would be far beyond the main idea of the present paper; it is sufficient to understand the message derivable from consideration of Table 7.

Although formal concept analysis can conceptionally be applied to continuous indicators, the very theory needs discrete values. Hence, application of FCA, as in the case of twenty-eight nations of the EU, needs discretization. This can be done in various ways [21], which may be controversial as discussed by Kerber and Bruggemann [24,32]. In the present case, it is not possible to present the pros and cons; instead the data are simply transformed by:

$$\mathrm{qbin}(j,x)\left\{\begin{array}{l} = 1 \text{ when } q(j,x) >= \text{mean}(j)\ (\text{take over the values of } q(j) \text{ of all objects} \\ \\ = 0 \text{ else} \end{array}\right\}$$

The resulting data matrix is given in Appendix B.

As an illustrative example, data from the 2015 Fragile State Index [33] for the 28 EU member states (i.e., prior to Brexit) were studied (see Appendix A). The Fragile State Index applies 12 indicators for the evaluation of single nations and is comprised of **Social indicators** (d1: Mounting Demographic Pressures, d2: Massive Movement of Refugees or Internally Displaced Persons, d3: Legacy of Vengeance-Seeking Group Grievance or Group Paranoia, d4: Chronic and Sustained Human Flight); **Economic indicators** (d5: Uneven Economic Development Along Group Lines, d6: Sharp and/or Severe Economic Decline); and **Political/Military Indicators** (d7: Criminalization and/or Delegitimization of the State, d8: Progressive Deterioration of Public Services, d9: Suspension of the Rule of Law and Widespread Violation of Human Rights, d10: Security Apparatus Operates as a "State within a State", d11: Rise of Factionalized Elites, d12: Intervention of Other States or External Political Actors) [34]. For a detailed description of the actual subjects being covered by the single descriptors, Baker [35] and/or The Fund for Peace [36] should be consulted.

Applying the 2015 data for the 28 member states of the EU under the 12 indicators, an approach similar to the above demonstrated by Table 7 leads to the following list (Table 8), where the notation should be read as—example—No 25, where "25" is an enumeration and does not have a contextual meaning, "7" is the number of objects for which the implication is realized, and "d9 d11 and → d7" indicates that when an object, here a nation "has" the property d9 and d11, then it also has the property d7.

Table 8. List of implications for the binary data, obtained by application of Equation (7).

No.	No of Objects	Realizations		Implications
1	6	d1 d2	→	d7
2	5	d1 d3	→	d7 d10 d11
3	9	d4	→	d7
4	4	d1 d6	→	d7 d9 d10
5	4	d2 d6	→	d7 d9
6	8	d3 d7	→	d11
7	8	d5 d7	→	d8
8	6	d1 d4 d7	→	d8
9	6	d1 d8	→	d4 d7
10	6	d2 d8	→	d4 d7
11	7	d3 d8	→	d5 d7 d11
12	8	d5 d8	→	d7
13	6	d1 d9	→	d7
14	7	d2 d9	→	d7
15	7	d7 d8 d9	→	d4
16	8	d10	→	d7
17	6	d7 d8 d10	→	d5
18	4	d6 d7 d9 d10	→	d1
19	6	d1 d11	→	d7
20	6	d2 d11	→	d7
21	8	d3 d11	→	d7
22	7	d5 d11	→	d3 d7 d8
23	7	d4 d7 d11	→	d8
24	9	d8 d11	→	d7
25	7	d9 d11	→	d7
26	5	d6 d7 d9 d11	→	d3
27	6	d7 d10 d11	→	d3
28	4	d3 d7 d9 d10 d11	→	d1
29	4	d2 d3 d7 d10 d11	→	d1
30	8	d12	→	d4 d7
31	7	d4 d7 d8 d12	→	d5
32	5	d1 d5	→	d4 d7 d8 d10 d12
33	5	d2 d5	→	d4 d7 d8 d12
34	5	d4 d6 d7	→	d5 d8 d9 d12
35	7	d4 d5 d7 d8	→	d12
36	6	d4 d7 d10	→	d12
37	5	d4 d5 d7 d8 d10 d12	→	d1

In Table 7, from four objects, only two realize the implication q1bin → q2bin. In Table 8, the maximum and minimum of realizations are 9 (#24) and 4 (#18, #28, #29), respectively. Hence, this number indicates how important the generated implication is for the dataset under consideration.

More complex implications can be found, i.e., 22 with seven objects with two realizations (d5, d11) having three implications → (d3, d7, d8), which means that when objects simultaneously have d5 and d11 then they also have d3, d7 and d8. Back to the original data, this translates to when nations have values in d5 and d11 that are larger than the mean values of d5 and d11, respectively, they also have larger values in the three indicators d3, d7 and d8 in comparison to the respective mean values. Note that in contrast to correlation analysis, the implications shown in Table 8 are directed. Correlation measures are symmetrical; orientation requires a contextual analysis.

A couple of concrete examples illustrate the contextual interpretation of some implications, e.g., #1, where we find six countries scoring high, i.e., above average, for the indicators d1 (Mounting Demographic Pressures) and d2 (Massive Movement of Refugees or Internally Displaced Persons), indicating that countries scoring high on these indicators also will score, maybe not surprisingly, high on indicator d7 (Criminalization and/or Delegitimization of the State). A further example would be (cf. #30) that countries scoring high on d12 (Intervention of Other States or External Political Actors) causes high scores on d4 (Chronic and Sustained Human Flight) and d7 (Criminalization and/or Delegitimization of the State). In-depth analysis of all the above implications (Table 8) is outside the scope of this paper.

In some sense, the generation of implications is done artificially, which means that

(1) the implication is to be considered a hypothesis, as it is only related to a sample;
(2) any implication urgently needs a contextual interpretation;
(3) any other discretization, say to d values, can change the result.

It should, however, be noted that these critical remarks are also relevant when statistical tools such as correlation or regression analysis are performed. The advantage of statistics is that it provides tests to evaluate the results (inference statistics). The mathematical method of partial order (and of lattice theory) is young, so it can be hoped that something such as inference methods will also be available in the future.

6. Conclusions and Outlook

6.1. Conclusions

Back to the preliminary conclusion

A preliminary conclusion was given at the end of the introduction. Now the question arises: Do we have to change this conclusion after demonstrating the application of partial order on MIS through examples from chemistry and sociology? The answer is: No. The use of diagrams is especially helpful to get deeper insight into the decision process. Mathematical concepts, namely comparability and incomparability, are at the heart of partial order theory applied to MIS. It is worthwhile to repeat the meaning of both of these concepts as "take-home messages":

Take-home message

- **Comparability**: An increase in an indicator value is always accompanied by a non-decrease of all other indicators. For decision making, an overwhelming number of comparabilities is a comfortable situation, as a ranking is almost found. When all n objects are mutually comparable, then the limit of a ranking is reached.
- **Incomparabilty**: An increase in the values of some indicators is accompanied by a decrease of some others. This expresses a conflict because a preferred state due to some indicators is weakened by unpreferred values of other indicators. The evidence of conflicts is smashed out by aggregation methods to obtain a single quantity, which allows a ranking. However, in a public audit there is a great deal of resistance explainable by the loss of information about the inherent conflicts.

How to extend the framework of partial order theory?

When the number of incomparabilities overwhelms comparabilities, the situation becomes uncomfortable from a partial order point of view. This is certainly one reason why partial order concepts are ignored in many MCDAs. Very often, this unhandsome situation is the consequence of inherent trade-offs within the decision; thus, it may be wise to include qualitative knowledge of stakeholders. To our knowledge, most MCDAs include the knowledge of stakeholders. However, the methods are often so tricky that, once again, there is no real understanding by people involved in the decision process. Then, the simplest technique comes into play, i.e., the weighted sum. Although this concept is to be criticized because of compensation effect, and because "suddenly" performing the summing, the qualitative nature of weights must be ignored. In other words, weighted sums have

- an advantage, because they can be understood, but they have three
- disadvantages, namely:
  - compensation effects,
  - uncertainty in the weights themselves, "Is aspect x really more important than aspect y?", and

- ○ need of a numerical representation of qualitative knowledge by weights.

Here, the concept of an operator G may be helpful. Varying the weights, at least in discussing the result of a decision support system, is not new. However, condensing the different options of weighting into an operator, called G, infers a new quality: Now the manifold of points of view about weighting can be evaluated by examining G as a whole. Although the concept of G has some inherent difficulties (scaling level of data, i.e., as to how far it is acceptable to combine ordinal data with weights to obtain a sum), it may solve the problem of uncertainty of weights, but obviously not that of compensation. So what?

Independent of which of the many MCDA-methods is selected, it is recommended that the decision problem is checked by partial order methods; hence, often, but not always, a decision has already been found.

6.2. Limitations and Outlook

Clearly, partial order theory is relatively young (in comparison to statistics) and needs for its application on MIS further research.

(1) The problem of noisy data is algorithmically solved; however, there is still the need of tests guaranteeing that there is a high probability for typical partial order theoretical results, such as "being a maximal element". Up to now, only the relational point of view is considered. However, when the data matrix has noisy data, then there must be a statement possible such as: There is a probability of, e.g., p% that an object is a maximal element.

(2) The above-mentioned problem of the scaling level of data. This problem can be circumvented by establishing preference functions (as done in many MCDA methods). Accepting the need to establish preference functions opens the door to many subsequent questions, such as: Which kind of preference function? How robust is the preference function in a statistical sense?

(3) When partial order is applied on a MIS (without the use of matrix G), then the interpretation of incomparabilities can be directly traced back to single indicator values. However, when a new MIS is constructed in accordance with Equation (7), remaining incomparabilities are caused by two influences: (a) indicator values and (b) weights. An attempt to solve this problem is under work.

(4) Partial order theory provides its own concept to obtain a weak order (average ranking). Although this concept is not specifically mentioned here, it plays a role as a mean for comparisons. How far does final ranking coincide with that provided by partial ordering? When this question appears, a subsequent problem arises: How far is any approximative construction of linear orders out of a poset exact? An exact linear ordering is most often computationally not tractable; hence, good approximations are needed.

(5) Partial order theory delivers mathematical concepts. Many of them seem to have a seed for useful application with MIS. Identifying these and checking their role for application with MIS is a permanent task, as mathematicians really do not sleep!

7. Further Reading

Partial order methodology has, over the years, been applied in a variety of disciples, comprised of theory and mathematics [17,20,24,31,37–53], decision support systems [54–70], biology and chemistry [71–94], formal concept analysis [95–97], sociology and economics [98–120], management (in its broadest sense) [121–137] and software [25–28,138].

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Appendix A

Original data adopted from the 2015 Fragile State Index.

Country	d1	d2	d3	d4	d5	d6	d7	d8	d9	d10	d11	d12
Cyprus	4	4.5	7	4.5	6.4	6.7	5.3	3	3.3	4.4	7.9	9.2
Bulgaria	4.2	3.5	5.2	4.6	4.9	6.2	5	4.2	3.4	4.1	5.3	4.8
Romania	3.7	2.7	6.8	4.5	4.7	5.2	5.6	4.3	3.9	3.5	5.2	4.1
Greece	3.6	1.6	5	3.8	4.2	6.5	6.5	3.9	3.4	4.5	3.7	5.9
Croatia	3.6	4.9	5.7	4.5	3.8	5.3	3.4	2.9	4.1	4	4.4	4.4
Hungary	2.3	2.5	4.7	3.3	4.3	5.9	6.6	3.3	4.5	2.4	5.3	4
Latvia	3.4	2.9	7.4	4.4	4.6	4	3.9	3.4	3	3.5	4.3	3.8
Estonia	3.3	2.9	6.5	3.5	3.7	3.6	3.2	3.4	2	3.1	5.5	3.1
Italy	3.1	3.7	4.9	2	3.4	5.6	4.2	2.3	2.5	4.4	4.9	2.2
Lithuania	3.3	2.6	4.3	4.2	5	5	3.2	4	2.4	3	3	3
Slovakia	2.8	2	5.9	4.2	4	5.1	3.7	2.9	2.7	2.3	3.7	3.3
Malta	2.8	4.6	3.9	4	2.9	4.2	3.9	2.3	3.3	3.4	2	3.6
Spain	2.5	1.7	5.8	2.4	4	5	3.3	2.7	1.9	3.3	6.1	2.2
Poland	3.3	2.8	4.4	4.4	3.5	4.1	3.2	2.8	2.5	2.3	3.8	2.7
Czech Rep.	1.9	2	3.8	2.8	3.2	4.8	4.2	3.1	2.1	2.6	4.3	2.6
France	2.8	2.2	6.8	2.2	3.7	4.8	1.8	1.5	2.3	2.3	1.9	1.4
United King.	2.6	2.4	5.6	2.1	3.7	3.9	2	2.1	1.8	2.5	3.5	1.2
Slovenia	2.8	1.4	3.9	2.8	3.9	4.2	2.6	2	2	2.1	1.6	2.3
Belgium	2.5	1.6	4.1	1.9	3.2	4.5	1.9	2.1	1.2	2	3.9	1.5
Portugal	2.6	1.6	2.6	2.2	2.9	5.1	1.8	2.7	2.3	1.6	1.8	2.5
Germany	2.5	3	4.6	2.1	3.3	2.9	1.2	1.6	1.5	2.1	2	1.3
Netherlands	3	2.1	3.9	2.6	2.7	3.4	1	1.5	1	1.8	2.6	1.2
Austria	2.4	2	4.3	1.5	3.4	2.2	1.4	1.6	1.7	1.1	2.7	1.7
Ireland	2.2	1.4	1.9	2.8	2.7	4.1	1.5	1.9	1.2	1.8	1.3	1.9
Luxembourg	1.7	1.7	3.1	2.1	1.5	1.5	1.3	1.3	1	2	3.4	1.6
Denmark	2.5	1.4	3.6	1.9	2.1	2.5	0.5	1.4	1.3	1.5	1.4	1.4
Norway	2.5	2.3	1.3	1.5	1.8	2.3	1	1.6	1	2.1	1.8	1
Sweden	1.5	1.5	1.6	2.3	1	3.8	0.5	1.2	0.9	1.4	1.1	1

Appendix B

The discretized (binary) data from the 2015 Fragile State Index (cf. Equation (7)).

Country	d1	d2	d3	d4	d5	d6	d7	d8	d9	d10	d11	d12
Cyprus	1	1	1	1	1	1	1	1	1	1	1	1
Bulgaria	1	1	1	1	1	1	1	1	1	1	1	1
Romania	1	1	1	1	1	1	1	1	1	1	1	1
Greece	1	0	1	1	1	1	1	1	1	1	1	1
Croatia	1	1	1	1	1	1	1	1	1	1	1	1
Hungary	0	1	1	1	1	1	1	1	1	0	1	1
Latvia	1	1	1	1	1	0	1	1	1	1	1	1
Estonia	1	1	1	1	1	0	1	1	0	1	1	1
Italy	1	1	1	0	0	1	1	0	1	1	1	0
Lithuania	1	1	0	1	1	1	1	1	1	1	0	1
Slovakia	0	0	1	1	1	1	1	1	1	0	1	1
Malta	0	1	0	1	0	0	1	0	1	1	0	1
Spain	0	0	1	0	1	1	1	1	0	1	1	0
Poland	1	1	0	1	0	0	1	1	1	0	1	0
Czech Rep	0	0	0	0	0	1	1	1	0	0	1	0
France	0	0	1	0	1	1	0	0	1	0	0	0
United King.	0	0	1	0	1	0	0	0	0	0	0	0
Slovenia	0	0	0	0	1	0	0	0	0	0	0	0
Belgium	0	0	0	0	0	1	0	0	0	0	1	0
Portugal	0	0	0	0	0	1	0	1	1	0	0	0
Germany	0	1	1	0	0	0	0	0	0	0	0	0
Netherlands	1	0	0	0	0	0	0	0	0	0	0	0
Austria	0	0	0	0	0	0	0	0	0	0	0	0
Ireland	0	0	0	0	0	0	0	0	0	0	0	0
Luxembourg	0	0	0	0	0	0	0	0	0	0	0	0
Denmark	0	0	0	0	0	0	0	0	0	0	0	0
Norway	0	0	0	0	0	0	0	0	0	0	0	0
Sweden	0	0	0	0	0	0	0	0	0	0	0	0

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standards

Article

Progress of Standardization of Urban Infrastructure in Smart City

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Abstract: After the Smart City initiative was put forward, cities all over the world started the pilot practice of developing Smart Cities. This triggered a series of thoughts: what is a Smart City, how do we determine the scope of work of a Smart City, and how do we formulate a new strategic agenda of the Smart City to make city smarter and more sustainable? The answer lies not only in finding Smart City solutions, but also leads to the research on the definition of Smart City terminology and the determination of corresponding tasks. Stakeholders of Smart City (e.g., policy makers, municipalities, solution providers, industry, and academia) develop technical and management standards for these tasks jointly. This paper reports the standardization planning on Smart City by the international standardization development organizations (SDOs), that is, the standardization framework of Smart City. It also presents one of the important aspects, namely, the progress of standardization activities on urban infrastructure that are being carried out by the International Telecommunication Union (ITU) via its Study Group 20, in supporting the adoption of information and communication technologies (ICTs) in Smart City. These standards include the classification of urban infrastructure, the interoperability between urban infrastructure and smart city platforms, and the requirements of detailed infrastructure from the perspective of ICT and the Internet of things (IoT). This paper also provides the use cases of application of some standards in global cities.

Keywords: information and communication technologies; internet of things; smart city; smart city platform; standardization; urban infrastructure

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1. Introduction

After IBM proposed a smarter planet in 2008 [1], many countries began to introduce the Smart City concept in urban construction. The Ministry of Science and Technology of China launched a Hi-Tech Research Programme project (the 863 Programme) in 2010 to start Smart City research and practice. As one of the two pilot cities of the project, the city of Wuhan launched a bidding procurement of the Wuhan Smart City conceptual design project in March 2011 [2] and a bidding procurement of the Wuhan Smart City master planning and design project in May 2011 [3], which might be the first Smart City commissioned research projects anywhere in the world. The purpose was to determine the concept of Smart City, and to clarify its scope of work and construction tasks. In particular, it was pointed out in the biddings that the design schemes were the basis and guiding documents for the subsequent construction and implementation of the Smart City pilot project. There were similar studies in Europe [4]. The concept of Smart City was introduced as a strategic device to encompass modern urban production factors within a common framework. Since then, more and more cities have begun master planning, design and pilot projects of Smart Cities [5]. The cities unanimously stressed the urgent need for Smart City standards. The rationale is as follows: without standards, the objectives of Smart City construction cannot be determined. If there are no unified standards, repeated construction and a waste of resources may not be avoided. Moreover, due to the lack of standards, it is difficult to evaluate the achievements of Smart City construction.

This urgent demand for standards has been partially responded to by some standards organizations, forums, and consortia. For example, the China Communications Standards Association (CCSA) started the exploration of standardization on Smart City and carried out some standard work items in 2012 [6]. ITU organized a forum on "Greener Smarter Better Cities" during "Green Standards Week" in September 2012 [7], and released a document "Call to Action on Smart Sustainable Cities". It invited stakeholders to create a focus group to analyse smart solutions that may be standardized, and to identify best practices that can facilitate the implementation of such solutions in cities. This has gradually opened up the standardization activities of Smart Cities.

In this paper, we summarize the international standardization activities on Smart City in Section 2, present the progress of standardization on urban infrastructure in Section 3, and provide use cases of application of some standards in global cities in Section 4.

2. International Standardization Activities on Smart City

2.1. Pre-Research on International Smart City Standardization

As a member of ITU Telecommunication Standardization Sector (ITU-T), we jointly proposed to establish the Focus Group on Smart Sustainable Cities (FG-SSC) in February 2013. The International Electrotechnical Commission (IEC) established the Smart City System Evaluation Group (IEC/SEG 1) in June 2013 and launched the Smart City strategy study in its Market Committee. The Information Technology Standardization Joint Technical Committee (ISO/IEC JTC 1) established the Smart City group at its plenary meeting in November 2013. The International Organization for Standardization (ISO) established the Advisory Group (AG) on Smart Cities at the plenary meeting of the Technology Management Bureau (TMB) in February 2014. The ISO Technical Committee for Sustainable Development of Communities/Sub Technical Committee for Infrastructure of Smart Communities (ISO/TC 268/SC 1) also carried out pre-research on the standardization of smart communities in the same period.

Usually, different standardization development organizations (SDOs) carry out standardization work on a hot topic in parallel. Given their expertise, they focus on different aspects of the standardization of Smart Cities. However, some duplication and overlap cannot be avoided. Through the establishment of an ISO-IEC-ITU joint Smart City task force (J-SCTF) [8], we coordinate our work in order to minimize duplication, as well as to propose the development of a common text.

2.2. Standardization Roadmap

Through the FG-SSC, ITU brought together experts from among its membership, including policymakers, academia, technical experts, representatives from the private sectors and other key stakeholders to formulate guidelines of constructing Smart Cities, as well as the needs of standardization [9].

The focus group put forward a series of work objectives, and also produced a series of achievements, in particular confirming the core role of ICT in Smart City construction [10]. Another outstanding achievement of the focus group was the definition of the term "Smart Sustainable Cities" (SSC) [11,12], which was later included in the vocabulary database of the ITU-T Standardization Committee for Vocabulary [13]. This definition has also been adopted by more than a dozen United Nations agencies, which coordinate the initiative of "United for Smart Sustainable Cities" (U4SSC) to promote global Smart Cities in achieving the UN Sustainable Development Goals [14].

We proposed a framework of standards for SSC (see Figure 1) in FG-SSC deliverables [15,16]. The SSC standards can be classified into four categories: (i) SSC management and assessment; (ii) SSC services; (iii) ICT; and (iv) buildings and physical infrastructure. We also proposed a standardization roadmap, taking into consideration the activities undertaken by the various SDOs, forums and consortia. The relevant standards and documents have also been collected and listed [17].

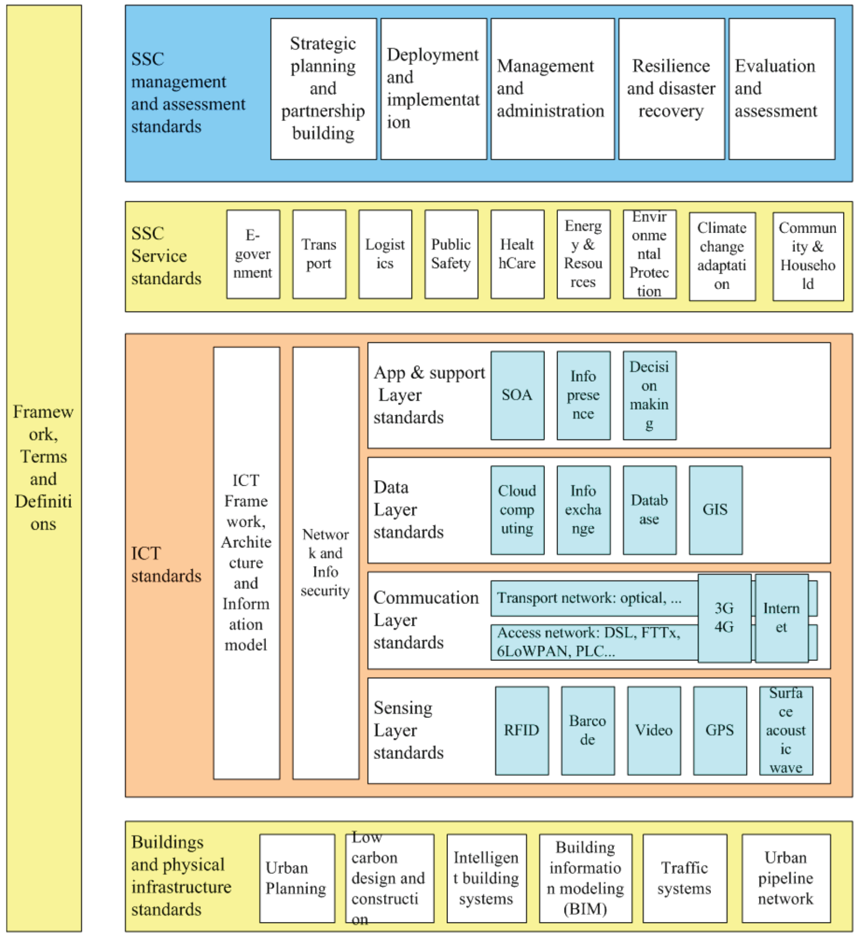

Figure 1. Framework of SSC standards.

The work of FG-SSC has concluded in May 2015 with 21 deliverables of Technical Reports and Technical Specifications on overview of SSC, SSC definition, city leaders' guide, master plan, stakeholder analysis, infrastructure, ICT architecture, cybersecurity, open data, smart building, smart water management, climate change adaptation, electromagnetic field consideration, integrated management, key performance indicators, and other matters [18].

2.3. ITU-T Study Group 20

The work of a focus group is usually continued by one or more study groups in the ITU-T. Established in 2015, the ITU-T Study Group 20, titled "Internet of Things and Smart Cities and Communities" (ITU-T SG20), is the leading study group on IoT and its applications, as well as Smart Cities and Communities. Currently, SG20 has seven Questions under study [19].

Table 1 lists ITU-T SG20′s key standardization areas in IoT and Smart Sustainable Cities [16,19]. Each category contains multiple international standards developed by SG20 that support the deployment of ICT in SSC.

Table 1. ITU-T SG20 key standardization areas in IoT and Smart Sustainable Cities.

ITU-T Y.4000 Series	Category
Y.4000–Y.4049	General
Y.4050–Y.4099	Definitions and terminologies
Y.4100–Y.4249	Requirements and use cases
Y.4250–Y.4399	Infrastructure, connectivity and networks
Y.4400–Y.4549	Frameworks, architectures and protocols
Y.4550–Y.4699	Services, applications, computation and data processing
Y.4700–Y.4799	Management, control and performance
Y.4800–Y.4899	Identification and security
Y.4900–Y.4999	Evaluation and assessment

The flagship seminar of SG20, "Digital transformation of cities and communities", is a series of webinars organized by ITU, together with other organizations and United Nations agencies, running from September to December 2021 [20]. The purpose is to discuss topics related to the digital transformation for cities and communities and their standardization, and to investigate the expanding role of digital transformation in driving innovation, sustainable growth and inclusion, as well as to respond to crises in cities and communities.

2.4. Interoperability of Smart City Platforms and Urban Infrastructure

When SG20 was established, the new work items on Smart City standards were created in accordance to the standardization framework illustrated in Figure 1. Considering the importance of core ICT infrastructure in urban information construction, our team proposed a work item on Smart City ICT frameworks in October 2015, whereas the team from Spain proposed another work item on ICT systems for Smart City management in January 2016. After several meetings, SG20 created two work items on draft Recommendations on Smart City platforms (SCPs) and their interoperability. ITU-T published these two Recommendations on SCPs in February 2018 [21,22].

The urban information systems collect data about the status of the city. These systems are managed by different types of control systems (such as IoT platform, Supervisory Control and Data Acquisition (SCADA) system, Big Data platform, etc.). In most cases, these vertical systems are separated, non-standardized and closed, and it is difficult to share resources and data. By introducing a common Smart City platform, multiple vertical systems are integrated and optimized to provide interaction between urban information systems to support various functionalities of urban services and ensure the convenience, security and scalability of the platform [22].

An SCP integrates city platforms and systems (i.e., SCP functions) directly, or through open interfaces between SCP and external providers, to offer the urban operation and services supporting the functioning of the city services. These interfaces are shown in Figure 2 as red arrows, as detailed in the following list:

- Services interface, which connects the SCP's Services Support Functions and the external services and applications providers.
- Interoperability interface, which connects the SCP's Data/Knowledge Functions interoperability and the external database and computation systems.
- Acquisition interface—which connects the SCP's Acquisition/Interconnection Functions and the external sensing and infrastructure systems.

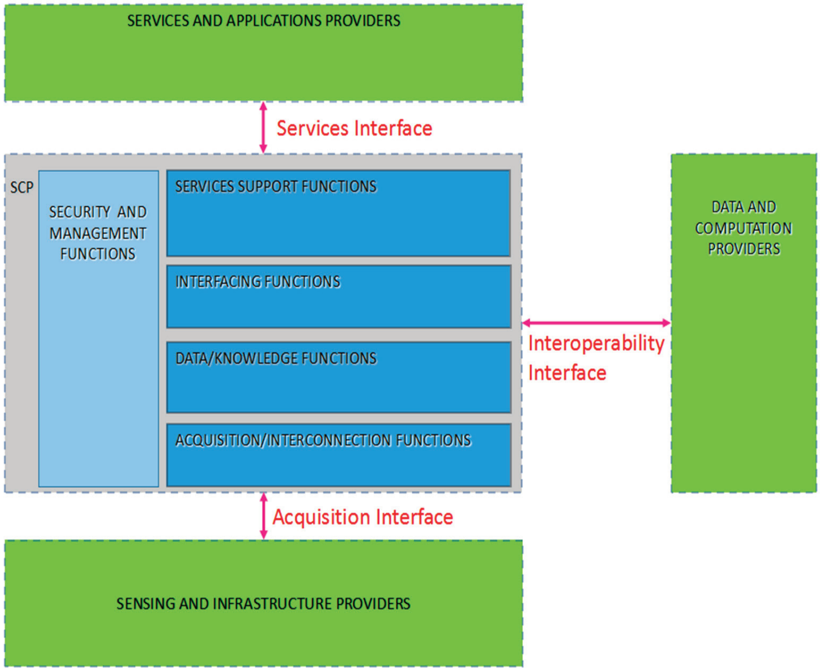

Figure 2. Reference framework of SCP.

3. Standards on Urban Infrastructure

When the Smart City goals were proposed, it was not clear how to improve the intelligent management through emerging technologies, or which urban infrastructure could be improved. We collected information on existing city infrastructure and released a technical report as a deliverable of FG-SSC [23], in order to figure out which infrastructure could be improved and which technology could be used. When SG20 develops standards based on relevant technical reports, we still need to answer a basic question: what is the definition of Smart City infrastructure? That is, what is the urban infrastructure within the scope of Smart City, and what is not? We then proposed a standard work item in October 2015—the overview of Smart City infrastructure [24]. This work item has lasted for a long time, and the content has been gradually enriched. Many work items have been derived. Consequently, urban infrastructure standardization has been expanded into a series.

Generally speaking, the urban infrastructure of Smart City should comprise man-made facilities. Naturally formed environments such as mountains, rivers, grasslands, forests, and lands are not urban infrastructure. The urban infrastructure of Smart City is identified as a variety of systems such as energy systems, water systems, transportation systems, communication systems, disaster risk-reduction systems, healthcare systems, and information transmission systems. Smart Cities need to use “intelligent” technologies to provide each physical infrastructure with “intelligence”, so as to improve the intelligence level of the overall urban infrastructure. At the city level, it needs to implement appropriate systems and measures in order to meet the United Nations’ Sustainable Development Goals [24,25].

Based on the architecture in Figure 2, ITU-T SG20 has issued, or is developing, a series of Recommendations, including definition and classification of urban infrastructure, management of urban assets, sensing and data collection system for city infrastructure, event monitoring for city infrastructure, and some specific application systems, such as civil engineering health management systems, construction site management systems, electricity infrastructure monitoring systems, fire water supply monitoring systems, and smoke detection monitoring systems.

3.1. Classification of Urban Infrastructure

In ITU, city infrastructure is defined as "the interconnected structures that enable people to get the resources they need in the city, and also the interconnected structures to provide public services for social and economic activities in the city" [24]. The basic infrastructures for building and operating SSC are categorized as:

- energy infrastructure;
- water supply and drainage infrastructure;
- transportation infrastructure;
- post and communication infrastructure;
- disaster risk-reduction infrastructure;
- cultural, sports and educational infrastructure;
- healthcare infrastructure; and
- social welfare infrastructure.

At city level, the infrastructure should be managed through ICT, and the sensing data can be collected by sensors deployed within these infrastructures.

3.2. Management of City Assets

From the perspective of assets, city infrastructure is also considered as a city asset [26]. The typical kinds of physical city assets may include, but are not limited to environmental sanitation facilities, water supply and drainage facilities, energy facilities, transportation facilities, postal and telecommunication facilities, and disaster risk-reduction facilities (shown in Figure 3).

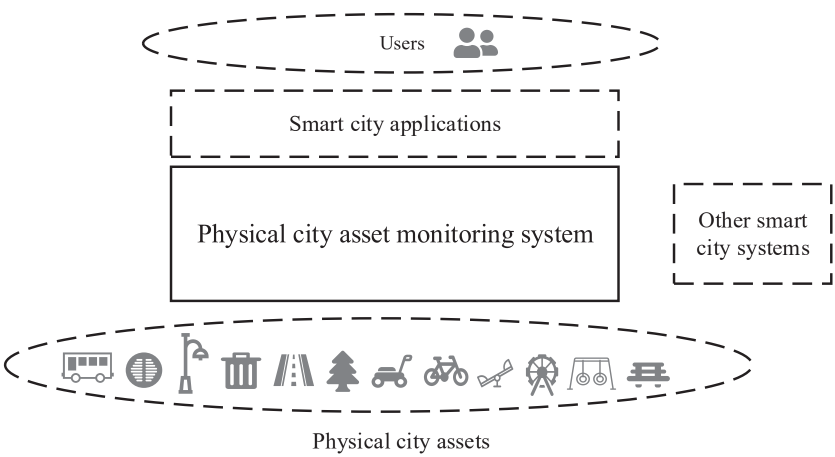

Figure 3. Overview diagram for physical city asset monitoring system.

Physical city assets keep evolving with technology and city development. With the support of IoT, the safeguarding, maintenance, and management of city assets can enable add a new service experience to the diversity of users, including, but not limited to, citizen and city asset operators.

The capability framework of city asset monitoring system is composed of city asset monitoring device capabilities, IoT device management capabilities, city asset monitoring service capabilities, network connectivity management capabilities, and identification capabilities.

3.3. *Sensing and Data Collection System for City Infrastructure*

Shown in Figure 4, sensing and infrastructure system consists of a sensing and data collection system (SDCS) and city infrastructures. An SDCS monitors the status and collects information of different kinds of city infrastructures, controls and manages the sensing devices attached to those city infrastructures, and provides corresponding information to SCP [24].

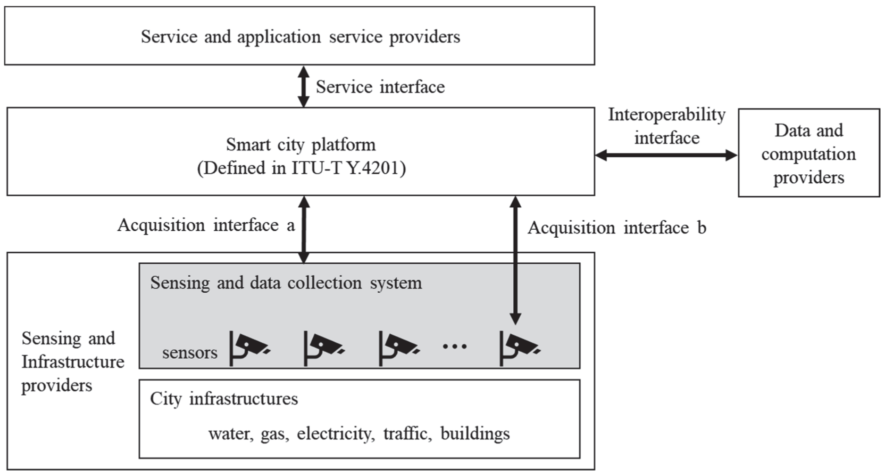

Figure 4. Interoperability of SCP and city infrastructure.

The SDCS can both provide the SCP with raw sensing data and can work as an agent to control and acquire data from a sensing device to the SCP. When the SCP acquires data directly from different kinds of sensing devices, the SDCS is working on transparent transmission mode and the sensing devices transmit data through the acquisition interface b to provide the SCP with raw sensing data. When there is a large deployment of sensing devices among city infrastructures, the SCP is unable to manage all the sensing devices. In such a case, the SDCS needs to be used as an agent to control and acquire data for the SCP, and it works on agent transmission mode and transmits processed sensing data via acquisition interface a.

3.4. *Event Monitoring for City Infrastructure*

Considering the needs of event monitoring of disasters, a disaster monitoring system (DMS) is defined and the DMS data are extracted from the sensing and data collection system (shown in Figure 5) [27]. The DMS aims to provide high-precision, multitemporal, and full-range sensing of disaster events. The structure and elements of sensing capabilities are described by a disaster monitoring metamodel [28].

This standard meets the two needs of the above SDCS when encountering specific disaster events: (1) to effectively discover the suitable sensors for specific disaster event from a large number of sensors; and (2) to collaborate with multiple sensors for disaster event monitoring.

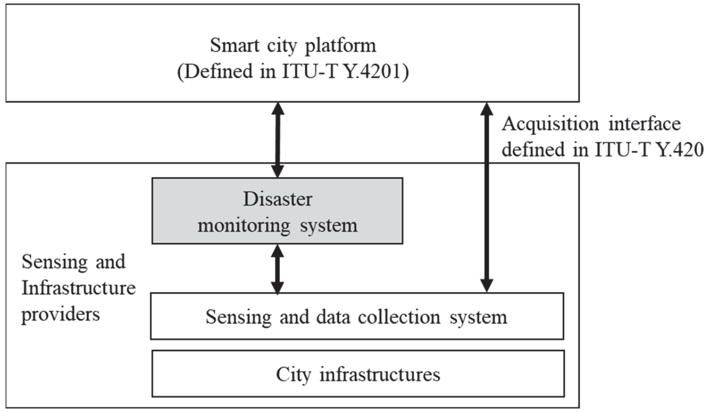

Figure 5. Interoperability of SCP, DMS, and city infrastructure.

3.5. Industry-Specific Infrastructure Monitoring

In addition to the general standards of urban infrastructure, SG20 has also formulated, or is developing, some standards for industry-specific infrastructure monitoring such as civil engineering infrastructure health monitoring, construction site management, electricity infrastructure monitoring, fire water supply monitoring, and smoke detection monitoring. These industry-specific standards usually have a common architecture, but they also have their own characteristics. By formulating and publishing these standards, the construction and maintenance of Smart Cities can be guided better.

3.5.1. Civil Engineering Infrastructure Health Monitoring

The civil engineering infrastructure refers to the large-scale structures that make up roads, bridges, and tunnels. The maintenance of civil engineering infrastructures is mainly based on periodic visual inspections and diagnoses by specialists to maintain the safety and integrity of the infrastructure. These specialists need a high degree of experience and technical know-how, as maintenance requires relevant human resource allocation and specific education and qualifications. Utilization of objective data collected from the civil engineering infrastructure using IoT capabilities leads to advanced and more efficient maintenance, while enhancing and rationalizing the human inspections and diagnostic work [29].

This Recommendation addresses IoT-based civil engineering infrastructure health-monitoring systems specifying the following:

- a reference model of IoT-based civil engineering infrastructure health monitoring systems; and
- requirements specific to IoT-based civil engineering infrastructure health-monitoring systems.

3.5.2. Smart Construction Site Management

Different from the monitoring of civil engineering infrastructure, smart construction site management focuses on the construction site scenario. It collects the information of construction processes through a smart construction site device (SCS-D) and transmits it to the smart construction site service platform (SCS-SP), so as to improve the construction process management, safety monitoring, and intelligent production [30].

SCS services are introduced to support users by achieving the following goals:

- to help realize the visualized and intelligent management of the construction project, by carrying out construction process trend predictions and emergency plans;
- to improve the level of information-based management of the construction project;

- to realize green construction and ecological construction;
- to potentially improve the modes of interaction, working, and management of any parties involved in the construction project;
- to eliminate potential waste of resources, and continuously improve the quality, scheduling, and cost of the project, with minimal resource input; and
- to maximize the benefit of the project, so as to meet the needs of customers and to ensure a maximized value.

3.5.3. Electric Power Infrastructure Monitoring

In electric power systems, electric power infrastructure (EPI) refers to the infrastructure in four processes, namely generation, conversion, transmission, and distribution of electricity. EPIs are complex and numerous in each process which requires different professional enterprises to carry out daily maintenance. The traditional daily maintenance of EPIs is based on regular inspection and diagnosis by specialists [31].

The objective of EPI health monitoring is to measure the health status of EPIs. By obtaining and analysing data, specialists can understand the change and development process of health status indicators over time. These health status quantities usually include temperature, humidity, deformation, insulation, fire protection, security, among others. An IoT-based electric power infrastructure monitoring system (IoT-EPIMS) is an advanced and efficient means to obtain the information and data required for the health maintenance of EPIs and an auxiliary means for the management of EPIs. Consequently, it can maintain the safe and stable operation of electric power systems and improve the comprehensive management level of power systems.

The scope of this Recommendation includes

- a reference model for IoT-based electric power infrastructure monitoring system;
- requirements specific to IoT-based electric power infrastructure-monitoring systems; and
- use cases of IoT-based electric power infrastructure-monitoring systems are provided in Abbreviations and Acronyms.

3.5.4. Monitoring of Water System for Smart Fire Protection

The water supply system is one of the most important parts of firefighting systems. The smart fire protection facilities based on IoT technologies are developed to monitor the water supply status in real time. It is required to accurately obtain the key data of a natural water source, a manmade water source, and a municipal fire hydrant. It will realize the digital management of fire extinguishing water source, providing reliable information for firefighting and rescue operations, enhance the availability of fire control information, and enable the on-site fire brigade to quickly develop targeted water supply plans [32].

This Recommendation introduces smart fire protection (SFP) and presents the monitoring of water systems (MWS) for SFP. This recommendation specifies requirements, functional architecture and functional components of MWS for SFP.

3.5.5. Smart Fire Smoke Detection

The fire smoke detection service is usually deployed in indoor environments such as residential buildings, factories, shopping malls, hotels, and office buildings. With the development of society and the economy, the fire smoke detection service is playing a more and more important role in people’s lives [33]. The smart fire smoke detection (SFSD) service not only detects smoke concentrations through sensors, and triggers a fire alarm when it reaches a certain threshold to prevent disaster, but also uses the network to send the alarm information to the cloud platform, thus notifying relevant departments and personnel in a timely manner through web/APP/SMS/voice/instant message client, and so on. The SFSD service can provide many benefits, including efficient maintenance and management, real-time alarm reports, real-time fault reports, and good service experience.

The scope of this Recommendation includes

- introduction to the SFSD service, including the issues of the traditional fire smoke detection service and the benefits of the SFSD service;
- requirements of the SFSD service for SFSD device capabilities and SFSD platform capabilities;
- functional architecture of SFSD devices and the SFSD platform within the SFSD service; and
- implementation and deployment model.

4. Use Cases of Standard Application

4.1. Use Cases of ITU-T Y.4900 Series

When developing, and after releasing, a standard, it is necessary to check whether it is applicable in practice. U4SSC can be regarded partly as an experimental and verification organization of ITU-T Smart City standards. By using ITU-T Y.4900 series standards [12,34–36], more than 150 cities around the world have evaluated and verified their achievements in Smart City construction, and provided U4SSC with verification reports [37].

It should be noted that Dubai, in cooperation with ITU-T FG-SSC in 2015, was the first city in the world to use FG-SSC Technical Specifications on KPIs [18] for SSC evaluation. In 2016, Singapore became the second to participate in the cooperation. Both cities have reported their practice on the SSC evaluation, especially the applicability of some indicators, which have enabled us to revise the series FG-SSC Technical Specifications on KPIs, and to make it a series of ITU-T Y.4900 Recommendations in 2016. Both Dubai and Singapore case studies can be downloaded from the ITU website [38].

4.2. Use Cases of ITU-T Y.4201 and Y.4200

ITU-T Y.4201 provides a set of high-level requirements that define the functionalities and interfaces of an SCP while ITU-T Y.4200 specifies the interoperability requirements of each function and interface listed in Y.4201 [21,22]. Both Recommendations advance sustainability and resilience in Smart Cities by providing the blueprint of an open and interoperable SCP that is capable of addressing a wide range of city challenges including but not limited to urban sensing, infrastructure management, climate change, and citizen-centered integrated services. Such a platform is the digital foundation for circulating data collected by different sensor networks and other sources and translating them into actionable insights that support city stakeholders in making better decisions.

In 2015, the provincial government of Hubei in China developed a Sharing Application Platform for Government Information Systems [39]. This information-sharing application platform was developed in accordance with the framework and specifications proposed in Y.4201 and Y.4200. The purpose of this platform is to coordinate captured data and apply them in order to improve city services. Through the Sharing Application Platforms of Government Information Systems, many of the isolated data silos have been eliminated. The work efficiency of the digital applications has been improved greatly. Since its construction in 2015, the platform has been instrumental in realizing the "digital government" vision of the Hubei Provincial Government. The platform is now actively involved in improving medical health, maximizing the efficiency of public transportation, monitoring upcoming extreme weather events, improving disaster management, and reinventing the education system along with other public services. At present, there are more than 700 digital government applications from more than 70 government departments running on this platform.

Benidorm in Spain is a popular tourist destination located close to the Mediterranean Sea. The city has a population of more than 75,000 and welcomes a huge number of vibrant visitors all year around. To enhance tourists' experience in the city, the government has implemented an intelligent management system, a Smart Destination Platform [40], for tourism that aims at using digital technologies to deliver tourism information in near real time. This Smart Destination Platform is constructed based on the specifications listed in Y.4201 and Y.4200. The smart platform is an open SCP that is able to receive information from a wide range of external communication sources including TripAdvisor, Twitter, and Airbnb. Collected data are then analyzed and redistributed to different city departments that would like to see an improvement in their water cycle, energy efficiency, traffic control, and other aspects of the city. The Smart Destination Platform has made remarkable improvements to the tourism industry in Benidorm. For example, the number of tourists attending sporting events has increased dramatically. Thanks to the information that is made available to them by analyzing real time data through the Smart Destination Platform, tourists are able to choose to attend their favorite sporting events, from running and cycling to soccer matches. The data gathered by the Smart Destination Platform also indicate that there is a strong demand for environmentally friendly commuting options in the city. At present, there are more than 24 other tourist destinations that have implemented this type of Smart City platform in Spain, thus fulfilling the country's vision of a digital future and its digital agenda.

In 2019, ITU applied the 2019 GEC Catalyst Awards of the Global Electronics Council based to these two standards and their applications in China, Spain and several other countries [41].

5. Conclusions

Rapid urbanization is the trend in most developing countries. At present, the investment in new infrastructure is far from over, and the developed countries are also facing challenges in the maintenance and upgrading of infrastructure. With the application of artificial intelligence and other technologies, Smart Cities have more available technologies. The goal of Smart City is not static. It will grow with the needs and development of economy and society, that is, the so-called "spiral rise".

So far, some framework standards of urban infrastructure have been published with the efforts of standardization carried out by the international SDOs, as well as the cooperation with some national standardization bodies and industrial standardization organizations. We expect an increasing number of stakeholders to participate in more standardization activities. For the prospect of infrastructure standardization, we look forward to the emergence of more and more detailed standards (such as data modeling and infrastructure anomaly detection) and urban infrastructure evaluation standards, so as to better implement the goal of "making cities and communities better".

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Abbreviations and Acronyms

This paper uses the following abbreviations and acronyms:

CCSA	China Communications Standards Association
DMS	Disaster Monitoring System
EPI	Electric Power Infrastructure
FG-SSC	Focus Group on Smart Sustainable Cities
IBM	International Business Machines Corporation
ICT	Information and Communication Technology
IEC	International Electrotechnical Commission
IEC/SEG 1	IEC Smart City System Evaluation Group
IoT	Internet of Things
IoT-EPIMS	IoT-based Electric Power Infrastructure Monitoring System
ISO	International Organization for Standardization
ISO/IEC JTC 1	ISO/IEC Information Technology Standardization Joint Technical Committee
ITU	International Telecommunication Union
ITU-T	ITU Telecommunication Standardization Sector
J-SCTF	ISO-IEC-ITU Joint Smart City Task Force
MWS	Monitoring of Water System
SCADA	Supervisory Control and Data Acquisition
SCP	Smart City Platform
SCS-D	Smart Construction Site Device
SCS-SP	Smart Construction Site Service Platform
SDCS	Sensing and Data Collection Systems
SDG	Sustainable Development Goal
SDOs	Standardization Development Organizations
SFP	Smart Fire Protection
SFSD	Smart Fire Smoke Detection
SG20	ITU-T Study Group 20
SSC	Smart Sustainable Cities
TMB	Technology Management Bureau
U4SSC	United for Smart Sustainable Cities
UN	United Nations

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Genetic Algorithms for Interior Comparative Optimization of Standard BCS Parameters in Selected Superconductors and High-Temperature Superconductors

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Abstract: Inverse least squares numerical optimization, 3D/4D interior optimization, and 3D/4D graphical optimization software and algorithm programming have been presented in a series of previous articles on the applications of the BCS theory of superconductivity and T_C dual/multiobjective optimizations. This study deals with the comparison/validation of the optimization results using several different methods, namely, classical inverse least squares (ILS), genetic algorithms (GA), 3D/4D interior optimization, and 2D/3D/4D graphical optimization techniques. The results comprise Tikhonov regularization algorithms and mathematical methods for all the research subjects. The findings of the mathematical programming for optimizing type I chrome isotope superconductors are validated with the genetic algorithms and compared to previous results of 3D/4D interior optimization. Additional rulings present a hypothesis of the new 'molecular effect' model/algorithm intended to be proven for Hg-cuprate-type high-temperature superconductors. In molecular effect optimization, inverse least squares and inverse least squares polynomial methods are applied with acceptable numerical and 2D graphical optimization solutions. For the BCS isotope effect and molecular effect, linearization logarithmic transformations for model formula software are implemented in specific programs. The solutions show accuracy with low programming residuals and confirm these findings. The results comprise two strands, the modeling for the isotope effect and molecular effect hypotheses and the development of genetic algorithms and inverse least squares-improved programming methods. Electronic physics applications in superconductors and high-temperature superconductors emerged from the rulings. Extrapolated applications for new modeling for the theory of superconductivity emerged from the numerical and image data obtained.

Keywords: interior optimization methods (IO); genetic algorithms (GA); graphical optimization; systems of nonlinear equations; Inverse Tikhonov regularization (ITR); objective function (OF); inverse least squares (ILS); electronic superconductors; high-temperature superconductors (HTSC); BCS theory

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1. Introduction

A superconductor can be defined as any material type whose electrical resistance is approximately null under specific thermodynamic and electromagnetic conditions. The essential thermodynamic conditions needed to reach the superconductivity state are given by a critical temperature T_C, beyond which, toward lower temperatures, a superconductivity effect takes place and interactions with magnetic fields constitute an important modifying factor. The T_C magnitude is around absolute zero Kelvin for conventional superconductors and approximately 100 degrees higher for high-temperature ones. Apart from this crucial condition, there are other physical ones. Namely, the maximum critical current, lower critical magnetic field H, and upper critical magnetic field H. Other factors are pressure and resistivity [1–10]. In general, the large variety of models and formulations within the theory of superconductivity, cause a multiple factor dependence that constrains the material superconductivity transition/effect [1–10]. The superconductor's principal physical-engineering advantage is its zero-energy loss for electrical currents. However, this excellent property for saving energy is not electromagnetically optimal. The benefit of null-conductivity energy loss is reduced by the necessary energy to cool the material to $-273°$. These antagonist constraints have to be optimized to obtain the most efficient total energy savings.

The current research/theoretical advances in superconductivity are profuse and wide-ranging [1–10]. Their mathematical background is extensive with several theoretical models, approximations, and equation variants [1–10]. At the atomic and molecular level, quantum mechanics and chemistry play a significant role in the basis for the theory of superconductivity [1–10].

High-temperature superconductors are those whose T_C is higher than 80 K. They have an unusually complex molecular composition and several varieties. In the classical BCS theory of superconductivity, the isotope effect model equation reads,

$$[M_i]^{\alpha} T_{Ci} - K \cong 0\,; \quad \text{for } i = 1, \ldots\ldots n\,; \tag{1}$$

where

K: Constant parameter. Range specific for every element.
M_i: Atomic mass (AMU) of any element isotope of (n) isotopes.
α: Constant parameter. Range specific for every element.
T_C: Critical temperature (K (usually) or C). Range specific for every element isotopes.
i: Corresponding isotope for every element.

In previous publications, the ILS method was used [1–12] and was based on the Tikhonov regularization theory. The principal difficulty of ILS in TR is the possibility of ill-posed matrices. This can be overcome automatically using modern programming systems, for example, singular value decompositions. The ILS with the L_2 norm set as the Tikhonov functions commonly reads

$$\text{minimize functional } J(\alpha), \quad J_{\alpha}(u)_{u \in \Re} = \|Au - K\|_2^2 + \alpha J(u); \tag{2}$$

where

J_α (u): Functions with regularization parameter alpha.
R: Real space.
u: Searched parameter solution.
A: Model matrix vector data.
K: Constant parameter matrix. Range specific for every element.
α: Constant parameter. Range specific for every element.
α1: Constant parameter. Tikhonov regularization parameter.
$\| \bullet \|_2$: L_2 Norm (at algorithm power 2).

These mathematical parameters have been described in [11–14]. A can be considered in this specific optimization as a model operator matrix. The second term multiplied by α is the regularization parameter. That is, J(u) is the regularization functional term usually related to smoothness, sparsity, and other specific characteristics of the α J (u). The norms are set as L_1 or L_2 for this research. Instead of using R (real numbers) spaces, the Tikhonov function can be set in Hilbert spaces or C (complex numbers) spaces. A matrix usually requires the decomposition of singular values for better calculations. Since Matlab subroutines have incorporated smoothness, it is taken as α = 0 for this study. This Tikhonov model function expressed in a simpler way was developed in previous contributions [2–6,11–15] with acceptable results.

The GA method is a stochastic optimization with differences compared to the ILS method. It is based on Darwin's theory [16,17] of natural selection. The species (parameters for OF minimization) whose genetic code (magnitudes) results in successful survival/adaptation (OF minimum value) in the environment are selected (parameters for following OF refinement). Therefore, at every step, a selective refinement is performed, discarding the genetic codes (OF parameter numbers) that do not fit the constraints. This process continues until the number of generations of and convergences to the constraints are achieved.

The objectives and innovations of this study were twofold, with the additional aims of the optimization of mathematical modeling and software engineering [1–5,18]. The first was to validate/compare the interior optimization method of previous contributions to genetic algorithm numerical and 3D graphical optimizations. The second was to attempt a tentative application of the isotope effect model of BCS theory on molecular HT superconductors with very similar compositions/molecular structures and critical temperatures. In that case, the model was designated as the molecular effect model. The results for both models were accurate and practical. The molecular effect model for the HTSC Hg-cuprates group showed a parabolic shape, and the T_C theoretical predictions based on this model were obtained. The 2D/3D/4D interior and graphical optimizations showed acceptable imaging and numerical results.

In summary, a comparative study of the different optimization methods was conducted for the chrome and selected HTSCs. The findings were numerically and graphically acceptable and accurate. The molecular effect model simulation results showed very low errors/residuals.

2. Mathematical and Computational Methods

Mathematical methods were based on the Tikhonov regularization theory with L_1 Chevyshev norms and L_2 inverse least squares optimizations [1–11,18]. Numerical data for the algorithm implementation is presented below followed by each method's calculations. Computational methods used were the classical inverse least squares (ILS) and genetic algorithms. ILS was set using several techniques and two norms, L_1 and L_2. Genetic algorithms method was implemented using an L_1 norm. Both optimization methods were intended to be used and the exponential model, logarithmic linearized model, and molecular effect model were optimized with the ILS polynomial-type Equations (1)–(8). The software structure and programming flow chart are explained in Diagram 1.

2.1. Numerical Data for Chrome and HTSC Hg-Cuprates

Table 1 shows the numerical data set for all the optimization methods and the two models used. The isotope effect model was applied for the chrome, 3D interior, and GA optimizations. The ILS method was used for the molecular effect model in the HTSC Hg-cuprates.

2.2. Mathematical Techniques and Inverse Least Squares Algorithms for Optimization Methods

The BCS isotope effect equation that was set for the optimizations based on Literature and previous studies [1–15] reads

$$[M_i]^{\alpha} T_{C_i} - K = 0; \tag{3}$$

where

K: Constant parameter. Range specific for every element.
M_i: Atomic mass (AMU) of any element isotope of (n) isotopes.
α: Constant parameter. Range specific for every element.
T_C: Critical temperature (K (usually) or C). Range specific for every element.
i: Corresponding isotope for every element.

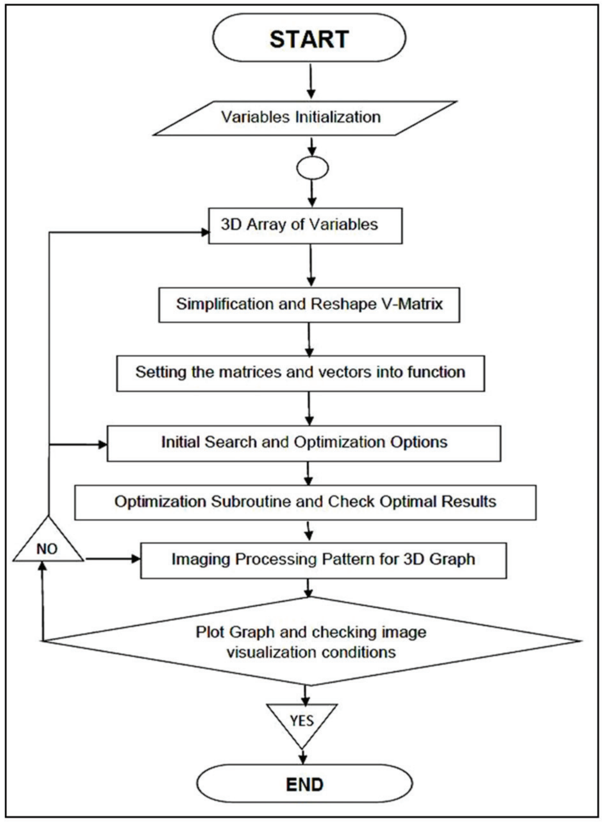

Diagram 1. Basic program structure for software. Optimization-specific programs differ for every method/algorithm in Equations (1)–(8). Software, loops, patterns, arrays, and imaging options are improved/developed and adapted on superconductor theory, from a long series of programming subsequent developments [3–11,19–27].

Table 1. Numerical data for Cr and HTSC Hg-cuprates.

NUMERICAL OPTIMIZATION DATA CHROME [SUPERCONDUCTOR, ISOTOPE EFFECT]		
Cr ISOTOPE TYPE BY ATOMIC MASS, (AMU)	**PERCENTAGE**	**APPROXIMATE T_C (Kelvin)**
52 (NATURAL)	83.789%	3
53	9.501%	3
54	2.365%	3
50	4.345%	3
NUMERICAL OPTIMIZATION DATA FOR Hg-CUPRATES [HT-SUPERCONDUCTOR, MOLECULAR EFFECT HYPOTHESIS]		
FORMULATION	**MOLECULAR WEIGHT (UAM)**	**APPROXIMATE T_C (Kelvin)**
$HgBa_2CuO_4$	602.7936	97
$HgBa_2CaCu_2O_6$	738.42	126
$HgBa_2Ca_2Cu_3O_8$	874.0432	133

Table 1. *Cont.*

NUMERICAL OPTIMIZATION DATA FOR Hg-CUPRATES [HT-SUPERCONDUCTOR, MOLECULAR EFFECT HYPOTHESIS]		
FORMULATION	**MOLECULAR WEIGHT (UAM)**	**APPROXIMATE T_C (Kelvin)**
$HgBa_2Ca_3Cu_4O_{10}$	1009.7	125
$HgBa_2Ca_4Cu_5O_{12}$	1145.3	110
$HgBa_2Ca_5Cu_6O_{14}$	1280.9	97
$HgBa_2Ca_6Cu_7O_{16}$	1416.54	88

However, unlike in previous publications [2–4], Equation (1) was also implemented in specific programs with a linear logarithmic transformation such as

$$\ln(T_{Ci}) + \alpha \ln(M_i) - \ln(K) = 0; \quad (4)$$

This linearization showed advantages and disadvantages in the precision of the optimizations. For the molecular effect model, the equation used for the ILS method with an L_1 Chevyshev norm reads

$$T_C\ (MO) \cong \sum_{i=0}^{i=N} a_i [MO]^i; \quad (5)$$

where,

MO: MO is the molecular mass of every compound in the HTSC group selected.
i: N degree of polynomial parameter power. Range [0, N].
a_i: Polynomial coefficient. Range [0, N].
T_C: Critical temperature (K (usually) or C) for each class of compound.

MO is the molecular mass of the HTSC group selected, in this study, the Hg-Cuprates group. With all these equations, the software algorithms were developed for the program's implementation. The discrete intervals selected for (i) were i ϵ [0, 5] and i ϵ [0, 6].

Therefore, based on previous formulas, there were two Tikhonov regularization algorithms applied for the ILS optimization of chrome. The first was the absolute OF value, that is, the Chevyshev L_1 norm. The second was with the L_2 norm for the Tikhonov function, that is, for the L_1 OF algorithm, reads

$$\begin{aligned}
&\text{minimize Tikhonov functional } J(\alpha), \\
&\text{with}\alpha 1 = 0\text{and } L_1 \text{ Chebyshev Norm}, \\
&J_\alpha(u)_{u\in\Re} = |Au - K|_{L_1} + [\alpha 1]J(u); \\
&\text{Hence minimize}, \\
&\left| [M_i]^\alpha T_C - K_i \right|_1 \text{ or} \\
&|\ln(T_C) + \alpha \ln(M_i) - \ln(K_i)|_1; \\
&\text{for } i = 1, \ldots n \\
&\text{subject to}, \\
&a \le M_i \le a_1; \\
&b \le T_C \le b_1; \\
&c \le K_i \le c_1; \\
&d \le \alpha \le d_1;
\end{aligned} \quad (6)$$

where

J_α (u): Function with regularization parameter alpha.
R: Real space.
u: Searched parameter solution.
A: Model matrix vector data.
K: Constant parameter matrix. Range specific for every element.
α: Constant parameter. Range specific for every element.

$\alpha 1$: Constant parameter. Tikhonov regularization parameter selected null.
$| \bullet |_1$: L_1 Chevshev norm (at an algorithm power of 1).
a, a_1: Constraint range specified in Table 1.
b, b_1: Constraint range specified in Table 1.
c, c_1: K optimization parameter range for the program, approximately [20.0, 50.0].
d, d_1: α constant range for the program, approximately [0.0001, 0.8].

The constraints a-d are applied for the optimizations [2–4,11,18]. The figure $\alpha 1$ is the Tikhonov regularization parameter. The mathematical concept for the regularization parameter's second term in the TR function means that the minimization of the principal term can reach a better defined/minimized global or local minimum. In other words, the vector/matrix u minimizes the principal term and also the regularization term that depends exclusively on u, which is the solution of the principal term. There is a range of function types for the regularization term [11–13]. This implies that the additional minimization of ($[\alpha 1] \times J(u)$) guarantees/attempts that the most convenient minimum among the minima is determined and is either a global or local minimum. According to the specific conditions for any specific problem, there is a large number of options for the regularization parameter [2–4,11,18].

Similar to Equation (6), the applied algorithm for the ILS with the L_2 norm reads

$$\begin{aligned}
&\text{minimize Tikhonov functional } J(\alpha),\\
&\text{with}\alpha 1 = 0 \text{ and } L_2 \ \text{ Norm},\\
&J_\alpha(u)_{u\in\Re} = \|Au - K\|_2^2 + [\alpha 1]J(u);\\
&\text{Hence minimize},\\
&\left\|[M_i]^\alpha T_C \ - K_i\right\|_2^2 \text{ or}\\
&\|\ln(T_C) + \alpha\ln(M_i) - \ln(K_i)\|_2^2;\\
&\text{for } i = 1,\ldots n\\
&\text{subject to},\\
&a \le M_i \le a_1;\\
&b \le T_C \le b_1;\\
&c \le K_i \le c_1;\\
&d \le \alpha \le d_1;
\end{aligned} \tag{7}$$

J_α (u): Function with regularization parameter alpha.
R: Real space.
u: Searched parameter solution.
A: Model matrix vector data.
K: Constant parameter matrix. Range specific for every element.
α: Constant parameter. Range specific for every element.
$\alpha 1$: Constant parameter. Tikhonov regularization parameter selected null.
$\| \bullet \|_2$: L_2 norm (at an algorithm power of 2).
a, a_1: Constraint range specified in Table 1.
b, b_1: Constraint range specified in Table 1.
c, c_1: K optimization parameter range for the program, approximately [20.0, 50.0].
d, d_1: α constant range for the program, approximately [0.0001, 0.8].

2.3. Hypothesis and Algorithms for Molecular Effect Model

The isotope effect model is based on the mathematical correlation between the atomic weight of every superconductor element isotope and the critical temperature Tc. This model has proven to be acceptable with some inaccuracies [2–10]. The molecular effect hypothesis proposed here that is mathematically and theoretically presented and numerically simulated is based on a similar modelling criterion, that is, that the HTSCs show several chemical groups whose molecular composition/formulation differ in their proportions of valences/elements [2–10]. From this theoretical basis, it is hypothesized that when deviations in the molecular weight due to proportional/isotopic variations in the molecule occur, there could be a mathematical model to predict the T_C magnitude change for each HTSC group element.

For this molecular model, the constraint values for the parameters are shown in Tables 1–4. The algorithms set for the ILS molecular effect model with a polynomial $p(MO_i)$ read

$$\begin{aligned}
&\text{minimize Tikhonov functional } J(\alpha),\\
&\text{with}\alpha 1 = 0\text{and } L_2 \text{ Norm},\\
&J_\alpha(u)_{u\in\Re} = \|Au - MO\|_2^2 + [\alpha 1]J(u);\\
&\text{Hence minimize},\\
&\|T_{Ci} - p(MO_i)\|_2^2 \text{ or}\\
&\|\ln(T_{Ci}) - p(\ln(MO_i))\|_2^2;\\
&\text{for } i = 1,\ldots n\\
&\text{subject to},\\
&a \le MO_i \le a_1;\\
&b \le T_{Ci} \le b_1;
\end{aligned} \tag{8}$$

J_α (u): Function with regularization parameter alpha.
R: Real space.
u: Searched parameter solution.
MO_i: Molecular mass for the HTSC cuprates from Table 1.
$P(MO_i)$: Polynomial optimization parameter matrix of HTSC cuprates range in Table 1.
$\alpha 1$: Constant parameter. Tikhonov regularization parameter, selected null.
$\| \bullet \|_2$: L_2 Norm (at an algorithm power of 2).
a, a_1: Constraint range specified in Table 1 for the HTSC cuprates.
b, b_1: Constraint range specified in Table 1 for the HTSC cuprates.

Table 2. Numerical results for Chrome using the GA optimization method.

NUMERICAL GA OPTIMIZATION RESULTS FOR CHROME FIRST STAGE		
Cr ISOTOPE TYPE RANGE (BY ATOMIC MASS, AMU)	K OPTIMAL	OBJECTIVE FUNCTION RESIDUAL (L_1 Chebyshev Optimization Norm)
[49, 55]	41.378132	176.23×10^{-9}
NUMERICAL GA OPTIMIZATION RESULTS FOR CHROME SECOND STAGE		
Cr ISOTOPE TYPE RANGE (BY ATOMIC MASS, AMU)	OPTIMAL ALPHA	OBJECTIVE FUNCTION RESIDUAL (L_1 Chebyshev Optimization Norm)
[49, 55]	0.6661	13.51×10^{-9}

Table 3. Numerical results for Chrome using the 3D interior optimization method.

NUMERICAL 3D/4D INTERIOR OPTIMIZATION RESULTS FOR CHROME FIRST STAGE		
Cr ISOTOPE TYPE RANGE (BY ATOMIC MASS, AMU)	K OPTIMAL	OBJECTIVE FUNCTION RESIDUAL (L_1 Chebyshev Optimization Norm)
[49, 55]	43.336596	7×10^{-3}
NUMERICAL 3D/4D INTERIOR OPTIMIZATION RESULTS FOR CHROME SECOND STAGE		
Cr ISOTOPE TYPE RANGE (BY ATOMIC MASS, AMU)	OPTIMAL ALPHA	OBJECTIVE FUNCTION RESIDUAL (L_1 Chebyshev Optimization Norm)
[49, 55]	0.6794	1×10^{-3}

Table 4. Numerical results for the ILS molecular effect model for Hg-cuprate HT superconductors.

NUMERICAL ILS RESULTS FOR MOLECULAR EFFECT MODEL FOR Hg-CUPRATES FIRST STAGE		
Hg-CUPRATES MOLECULE TYPE RANGE (BY MOLECULAR MASS, AMU)	OPTIMAL ALPHA	OBJECTIVE FUNCTION RESIDUAL (L_1 Chebyshev Optimization Norm, 3000 functions)
[738.42, 1416.54]	5.35×10^{-3}	9.704343
PROGRAMMING FIRST-STAGE DATA		
K	ALPHA	Tc
LOG [80, 150]	[0.0001, 1]	[88, 126]
NUMERICAL ILS RESULTS FOR MOLECULAR EFFECT MODEL FOR Hg-CUPRATES FIRST STAGE		
Hg-CUPRATES MOLECULE TYPE RANGE (BY MOLECULAR MASS, AMU)	OPTIMAL K	OBJECTIVE FUNCTION RESIDUAL (L_1 Chebyshev Optimization Norm, 3000 functions)
[738.42, 1416.54]	109.2585	10.45268
PROGRAMMING SECOND-STAGE DATA		
K	FIXED ALPHA	Tc
LOG [80, 150]	5.35×10^{-3}	[88, 126]

MO is the molecular weight of the HTSC selected (i) within an HTSC group and [a, b] are the constraint intervals from Table 1. The other parameters are described in Equations (1)–(7). The constraint values for the parameters are shown in Tables 1–4. All parameter details are described in Equations (1)–(7). OF was chosen either with/without algorithmic linearization, depending on the accuracy of the program results.

In previous publications, [3–6,19], the 2D/3D/4D interior and graphical optimization methods were presented. The authors' definitions of 2D/3D/4D interior optimization were stated:

Definition 1. *The interior graphical optimization method, [2–4,22] is a type of nonlinear optimization that combines the separation of variables method with stages of the 3D graphical optimization method.*

For all the algorithms presented in Equations (1)–(8), the 2D/3D/4D interior/graphical optimizations are calculated. The 2D/3D/4D interior optimization method is an improvement of the 3D graphical optimization method [2–4,19–27], set in this article related to superconductors theory [5–10]. Its base is a 2D/3D/4D imaging separation of variables in a series of stages. With the most favorable separation of variables, it is possible to optimize all the parameters throughout the subsequent stages of the 2D/3D/4D optimization plots. In every 2D/3D graph, the most convenient local, global, or semi-local minimum for every OF variable is chosen. The details of this method can be found in [2–4,12,22,26].

2.4. Genetic Algorithm (GA) Methods

In brief, the genetic algorithms (GA) optimization method has experienced a recent increase in the use of its optimization variants. Each one of these GA variants has its advantages and disadvantages [10,11]. GA is a stochastic mixed method similar to Monte Carlo but simpler/faster in general.

GA usually selects a randomly large number of successive generations for the objective function minima accuracy subject to constraints. For every generation, three types of choices are applied for the OF. Namely, elite selection, after-mutations, and cross-over changes in the variables' values. The GA method belongs to the stochastic optimization methods group. For instance, it is similar to the random, stochastic simulated annealing (SA) method [10,11,16–24,28]. However, SA cannot determine the global minimum and is stopped at a local minimum function concavity because of its proper algorithm. GA stops when the number of generations constrains and/or the numerical tolerance for a chromosome generation is reached even if that solution is a local or global minimum.

Another random method, Monte Carlo, has a more intensive global minimum search. Monte Carlo estimates the objective function minimum/minima parameters in search of a global minimum. If a global minimum exists, it does not stall easily at any local minima. The Monte Carlo search is exhaustive and this property causes the classical lateness of Monte Carlo. However, new Monte Carlo versions/software have overcome this issue. From a comparison of the genetic algorithm and Monte Carlo methods, the concept emerged that a stochastic optimization method for the development of life and biodiversity was invented and optimized by nature millions of years ago [10,11].

In this study, a simple GA constrained nonlinear optimization was performed. Imaging processing methods were set in some program areas to check/compare the numerical algorithm results. In every GA algorithm step, a numerical refinement was the approach to the OF. There are several variants of the GA method [16,17]. They have in common the steps of selection, mating, mutation, and final convergence. The type applied in this study was the continuous variables GA method, which uses a much larger range of variable numerical data [16,17]. The former decodes the chromosomes and evaluates the OF value for every chromosome in the initial stages. In this study, the continuous GA method was applied.

From Equations (1)–(8), the main difference between the ILS and GA methods can be seen, that is, that the ILS has a matrix with a fixed dataset. In the ILS, matrix A is set to reach the optimal vector matrix solution u for the system A u = K. On the contrary, the GA performs an extensive random search with a set of values that are numerically checked in each step. Those are proven to obtain better OF accuracy subject to constraints remaining throughout the running of the program. Both the GA and ILS methods can be considered useful for optimization; each one shows advantages and disadvantages. Actually, GA methods have been shown to obtain accurate results when the complexity and number of the variables and constraints in the OF increase. A classic example of the Monte Carlo stochastic method is the GEANT systems series, which is generally used in medical physics [25,28,29]. The GEANT4 software applies a large-scale random selection very similar to GA, for instance, to determine the optimal beam radiation parameters in intensity-modulated radiation therapy [28,29]. Both of these methods usually require a longer running time compared to ILS [2–4,13,17,19–27].

2.5. GA and Inverse Least Squares Computational Software

Diagram 1 shows the basic structure of the software that was used for programming Equations (1)–(8). The differences between each program are related to subroutines, patterns, loops, matrix definitions, imaging processing subroutines and options, and several others. Genetic algorithm programs [2–4,17] are significantly different but use the same technique. These programs constitute an advance/improvement on the previous studies [2–4,13,17,19–27]. All software for ILS and GA was adapted on superconductors applied theory, materials concepts, Isotope Effect, and optimization fundamentals [30–38].

3. Results

The results are divided into two models. The first group is the comparative optimization between the 3D interior optimization and genetic algorithm methods to validate the results of the previous studies for chrome and other superconductors materials [2–4], combined with recent concepts in applied mathematics on modeling and [2–4,39–41]. However, not all the superconductors applied theory are exactly/perfectly coincident along the literature [42–44]. The second group is the inverse least squares method for the hypothesis of the molecular effect model for selected HTSC Hg-cuprates. The numerical results, errors, optimization residuals, and 3D/4D graphics are presented. The running time is specified for each subsection, which is generally consistent with [2–4].

3.1. GA Numerical Results for Chrome

Table 2 shows the numerical results using the GA method in two stages as 3D interior optimization was also conducted. The results match well for both methods. The running time was about 4–8 s including the graphics (Intel Core 3).

3.2. Interior Tikhonov Optimization Numerical Results for Chrome

Table 3 presents the numerical results for 3D/4D interior optimization for chrome using the isotope effect objective function in logarithmic form. The running time was about 2–4 s including the graphics.

3.3. GA Interior Optimization 2D Graphical Results for Chrome

Figures 1–3 show the GA method results for chrome isotopes. The optimization was performed in two stages comprising the best fit, average distance among individuals, and stopping criteria.

3.4. Inverse 3D Interior Tikhonov Optimization Graphical Results for Chrome

The image processing method for the 3D interior optimization results for Chrome is shown in Figures 4–7. The numerical data that are presented in the Results section is pictured inset in the 3D charts.

3.5. Inverse Least Squares Numerical Results for HTSC Hg-Cuprates with Molecular Effect Model

The calculation using the ILS method for the molecular effect model was conducted with two types of programs. The first was a nonlinear ILS Matlab program based on subroutines. The second was an ILS based on a polynomial fit. The best results were obtained with the second program. Table 4 shows the results for the nonlinear ILS Matlab program. Tables 5 and 6 and Figures 8 and 9 show the results of the ILS polynomial molecular effect model for the HTSC Hg-cuprates. With both methods, the different models were proved, but the polynomial one performed the best. The running time for the ILS method was about 3–6 s, including the graphics, and about 2–5 s for the ILS polynomial method.

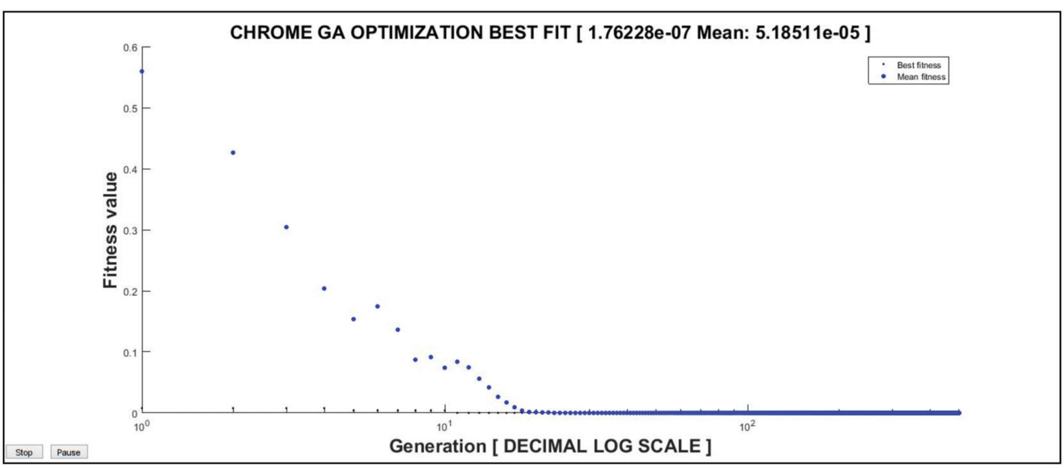

Figure 1. Chrome GA results (first stage of optimization) for best fit across generations (500). Results are accurate in magnitude orders. Best Fit results 1.76×10^{-7} and Mean 5.19×10^{-5}.

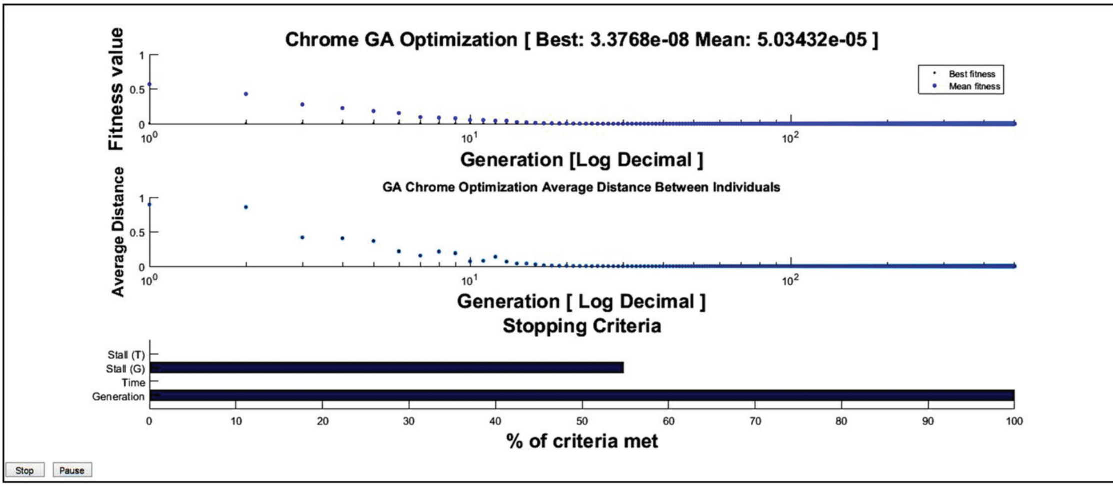

Figure 2. Chrome GA (first stage of optimization) combined chart results for best fit across generations (700). Best fit, average distance between individuals, and stopping criteria are shown. Results are accurate. Best Fit and Mean values are lower as it was selected 700 generations.

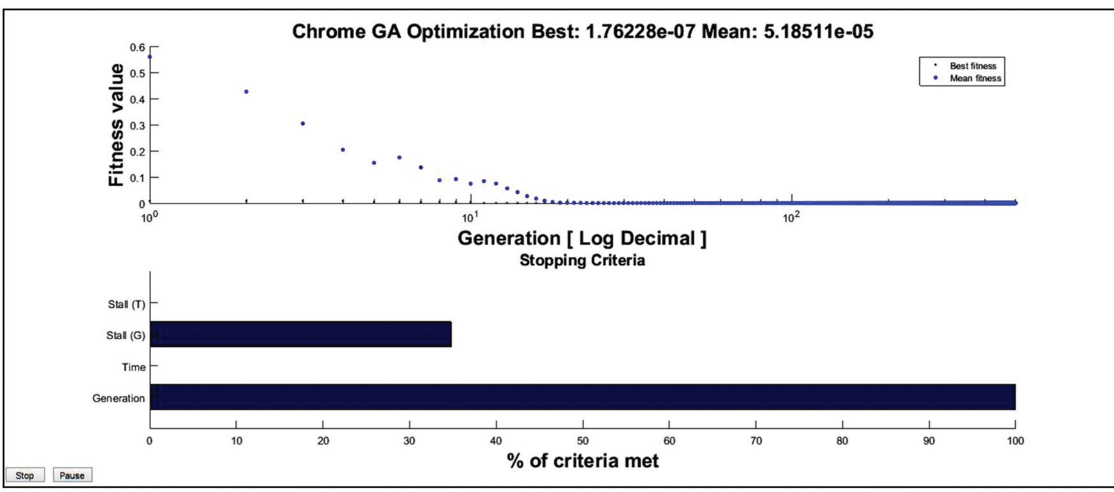

Figure 3. Chrome GA (second stage of optimization) combined chart results for best fit across generations (500) and stopping criteria. Results are accurate in magnitude orders. Best Fit results 1.76×10^{-7} and Mean 5.19×10^{-5}.

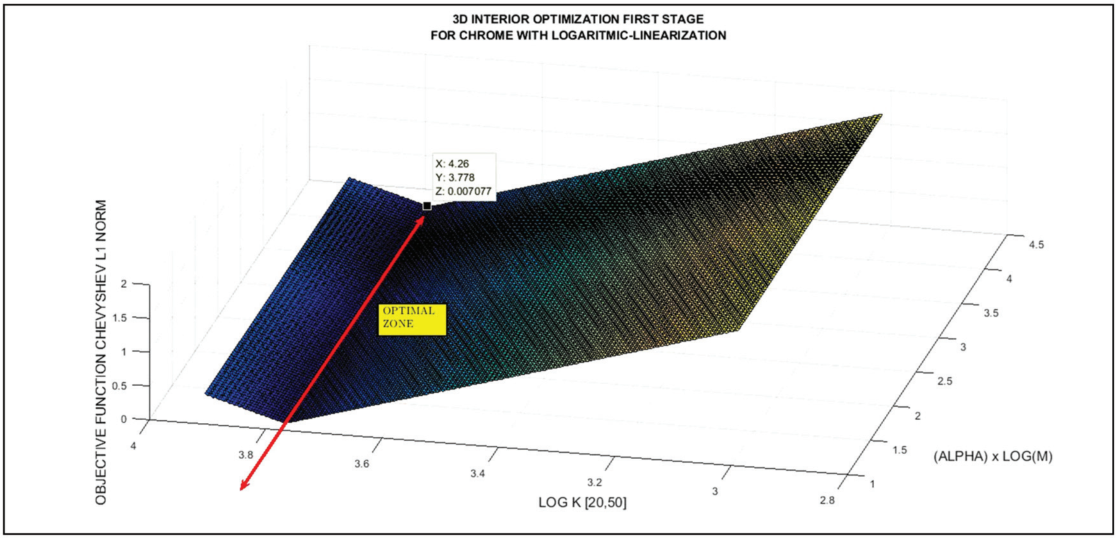

Figure 4. Chrome first stage of 3D interior optimization. Optimal zone is accurate and OF magnitude is about 7×10^{-3}. This value validates the chrome GA results. Optimal zone marked inset. Image processing method 1.

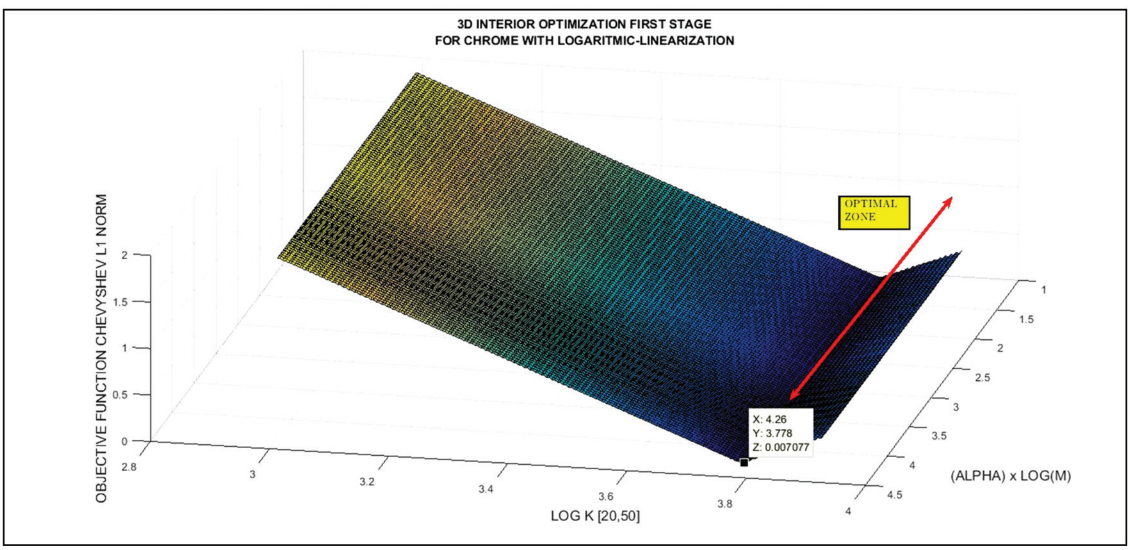

Figure 5. Another perspective of chrome first stage of 3D interior optimization. Optimal zone is accurate and residual is about 7×10^{-3}. This value validates the chrome GA results. Image processing method 1.

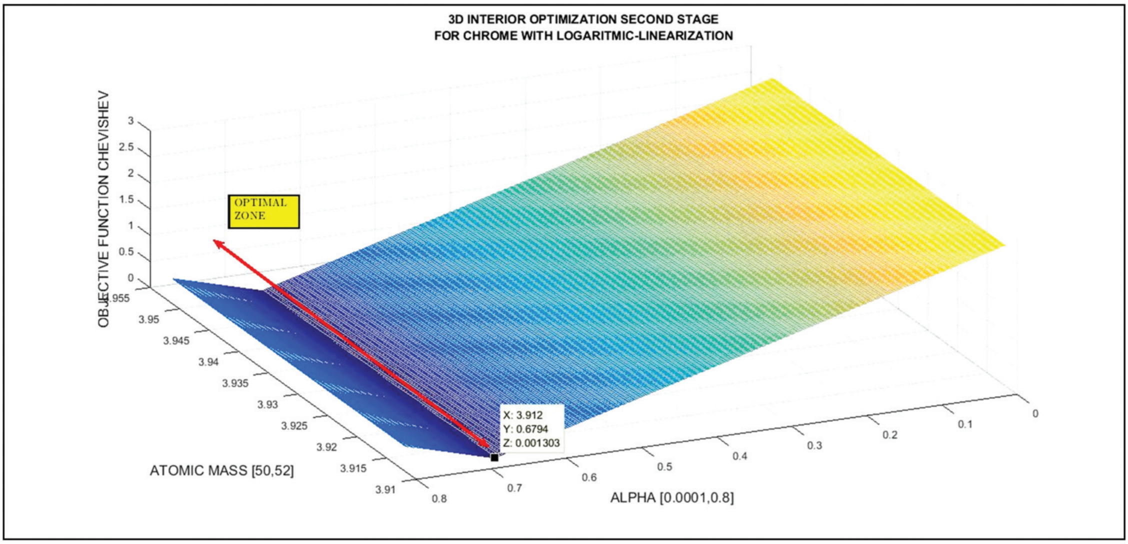

Figure 6. Chrome second stage of 3D interior optimization. Optimal zone is accurate and OF magnitude is about 1×10^{-3}. This value validates the chrome GA results. Subroutine for image processing is different from the first-stage 3D interior optimization charts. Image processing method 2.

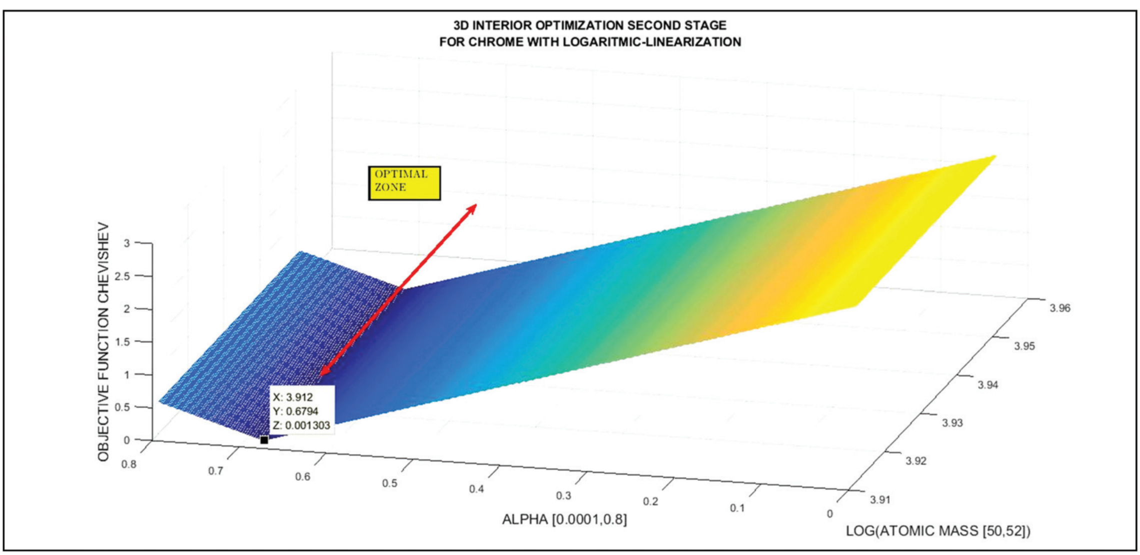

Figure 7. Another perspective for chrome second stage of 3D interior optimization. Optimal zone is accurate and OF magnitude is about 1×10^{-3}. This value validates the chrome GA results. Subroutine for image processing is different from the first-stage 3D interior optimization charts. Image processing method 2.

Table 5. Numerical results for the molecular effect model using the 6-degree polynomial method and the approximated equation. For the approximation, a quadratic polynomial is set.

ILS MOLECULAR EFFECT MODEL 2 (6-DEGREE)			
COEFFICIENT	VARIABLE X	COEFFICIENT APPROX	VARIABLE X SELECTED
-1.4683×10^3	CONSTANT	[−1.468]	CONSTANT
8.5713	X	[8.571]	X
-20.8471×10^{-3}	X^2	$[-20.847 \times 10^{-3}]$	X^2
29.0052×10^{-6}	X^3	$[29.005 \times 10^{-6}]$	X^3
-23.4857×10^{-9}	X^4	0	X^4
10.1448×10^{-12}	X^5	0	-
-1.7944×10^{-15}	X^6	0	-
RESIDUAL = 32.703892 × 10^{-12}			
APPROXIMATE POLYNOMIAL			
Tc = [−1.468] + [8.571] MO + [−20.847 × 10^{-3}] MO^2 + [29.005 × 10^{-6}] MO^3 + [−23 × 10^{-9}] MO^4			

Table 6. Numerical results for the molecular effect model using the 5-degree polynomial method and the approximated equation. For the approximation, a cubic polynomial is set.

ILS MOLECULAR EFFECT MODEL 2 (5-DEGREE)			
COEFFICIENT	VARIABLE X	COEFFICIENT APPROX	VARIABLE X SELECTED
4.8106	CONSTANT	[4.811]	CONSTANT
-982.4692×10^{-3}	X	$[-982.469 \times 10^{-3}]$	X
4.4871×10^{-3}	X^2	$[4.487 \times 10^{-3}]$	X^2
-6.1759×10^{-6}	X^3	$[-6176 \times 10^{-6}]$	X^3
3.5178×10^{-9}	X^4	0	-
$-725.5851 \times 10^{-15}$	X^5	0	-
RESIDUAL = 264.499782 × 10^{-3}			
APPROXIMATE POLYNOMIAL			
Tc = [4.811] + [−982.469 × 10^{-3}] MO + [4.487 × 10^{-3}] MO^2 + [−6176 × 10^{-6}] MO^3			

3.6. Numerical Results and Predictive Model Use Verification

The numerical validations/predictions of the optimization methods are presented in Tables 7–9. The validations are also given with the Tc and K predictions. For the molecular effect model, the 6-degree ILS numerical validation is shown in Table 9. Table 7 shows the validations/predictions for the GA chrome results. Table 8 presents the 3D/4D ILS interior optimization method validations/predictions for chrome. Table 9 shows the ILS validations/predictions for the molecular effect model for the HTSC Hg-cuprates.

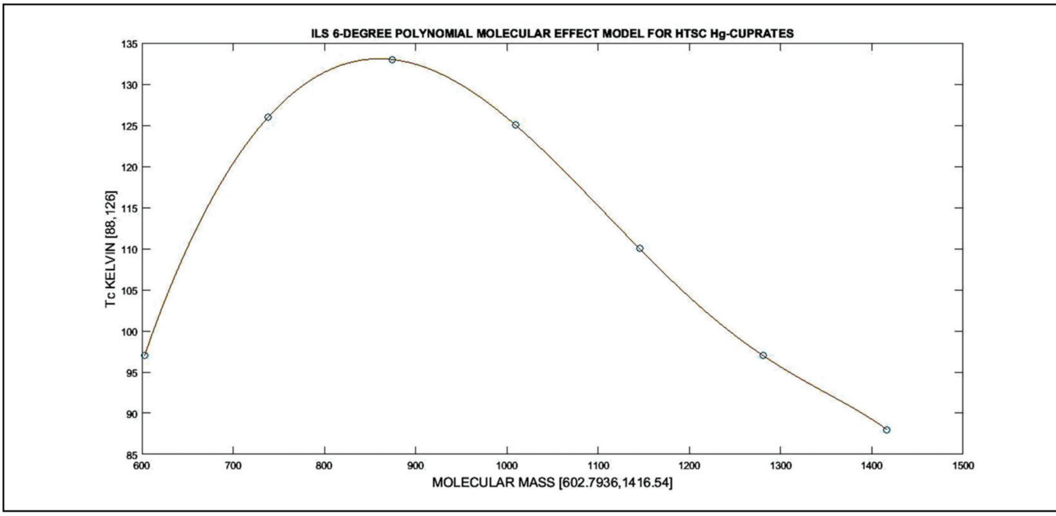

Figure 8. Molecular effect model with ILS 6-degree polynomial fit. Generally, Tc matches a parabolic curve when the molecular weight increases.

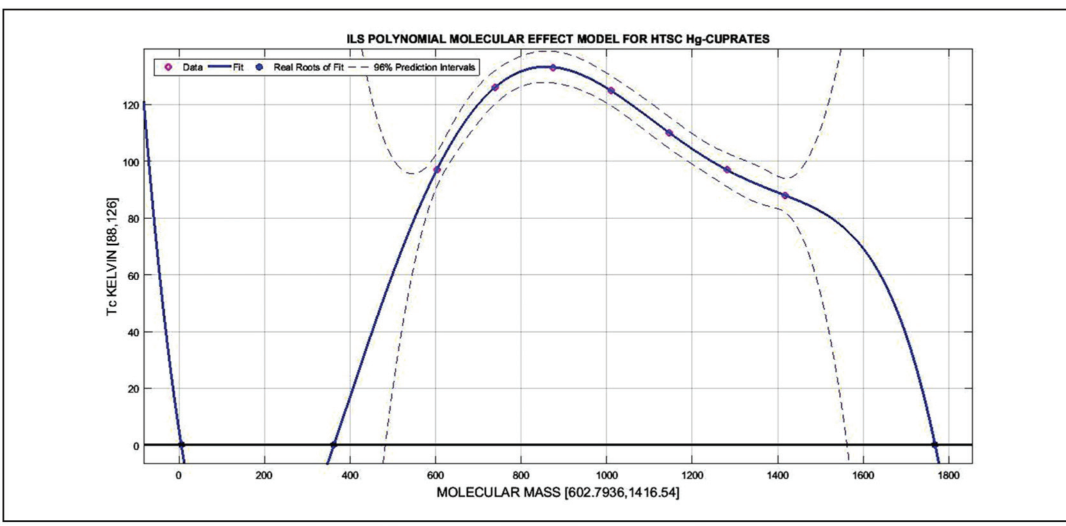

Figure 9. Molecular effect model with ILS 5-degree polynomial fit with 96% confidence intervals. Generally, Tc matches a parabolic curve when the molecular weight increases. At lower values of molecular weight, there is a low accuracy of approximately 250 toward lower molecular weight magnitude values.

Table 7. GA program numerical results validation for chrome isotope effect model. For UAM the errors decrease.

CHROME GA NUMERICAL VALIDATION		
ISOTOPE [UAM]	**K PREDICTED**	**K OPTIMAL BY GA**
50	40.6261	41.3781
51	41.1655	
52	41.7014	
53	42.2339	

Table 8. 3D/4D ILS interior optimization numerical validation program numerical results for chrome isotope effect model. For UAM, the errors decrease.

CHROME 3D/4D ILS INTERIOR OPTIMIZATION NUMERICAL VALIDATION		
ISOTOPE [UAM]	**K PREDICTED**	**K OPTIMAL BY ILS- INTERIOR OPTIMIZATION**
50	42.7958	43.3365
51	43.3755	
52	41.9512	
53	42.5240	

Table 9. Program numerical results for molecular effect model using 6-degree polynomial and approximated equation. Errors are almost null [10^{-12} magnitude order]. Numerical program results for validation simulation give acceptable Tc figures. In this program, MO varied and the corresponding Tc was predicted using the model.

PROGRAMMING RESULTS FOR ILS MOLECULAR EFFECT MODEL 2 (6-DEGREE)			
MOLECULAR WEIGHT (AMU)	Tc EXPERIMENTAL [K]	Tc PROGRAM PREDICTED [MO]	ERROR
602.7936	97	97.0000	9.3223×10^{-12}
738.42	126	126.0000	1.8190×10^{-12}
874.0432	133	133.0000	3.8654×10^{-12}
1009.7	125	125.0000	5.9117×10^{-12}
1145.3	110	110.0000	3.6380×10^{-12}
1280.9	97	97.0000	6.8212×10^{-13}
1416.54	88	88.0000	-2.6375×10^{-11}
NUMERICAL PROGRAM VALIDATION			
MO SIMULATED		**Tc PROGRAM PREDICTED**	
602.7936		97.0000	
750.42		127.3895	
890.0432		132.7059	
1029.7		123.0025	
1180.3		106.1526	
1295.9		95.9194	
1480.54		80.5684	

4. Electronics Physics and Engineering Applications

Applications of 2D/3D/4D interior and graphical optimizations [5–10,31–34,36–38,40–44] are in the field of the BCS theory of superconductivity in the isotope effect model. Further prospective applications for the molecular effect model in the HTSC groups of compounds are primarily considered for T_C predictions when HTSCs show several chemical groups whose molecular composition/formulation differs in proportion to the valences/elements [5–10,31–34,36–38,40–44].

5. Discussion and Conclusions

The objective of this research was to prove/show the similarities in the results of several optimization methods applied for chrome and the HTSC-Hg-cuprates group using the BCS theory of superconductivity [2–4]. For chrome, the methods were the genetic algorithms and 3D/4D interior optimization methods. For the HTSC Hg-cuprates group, a hypothesis for the molecular effect model was approached and numerically analyzed. The rationale for this molecular effect model was set based on the molecules' similar atomic weights (isotope variations in molecular composition and/or molecular approximate proportion/composition for any constituent element) for this HTSC group.

The basis for the molecular effect hypothesis has, therefore, several theoretical applications for Tc and its equation predictions. The first is a prediction of the approximate T_C for a molecule whose composition within the HTSC group differs in the valence/proportion of one/several elements. The second is the case where the molecule is formed by the different isotopes of some/one of its elements, for example, any Hg isotope with a different atomic weight. The third is the case when both the theoretical and experimental facts occur, that is, when both the valence/proportion of one/several elements form part of the molecule and the type of isotopes of the molecule's elements changes. Notably, this study sets a hypothesis/pre-hypothesis based on optimization predictions for the HTSC Hg-cuprates.

The results can be classified into numerical and 3D/2D graphical. The numerical results for the chrome isotope effect, both with GA and 3D/4D interior optimization, can be considered acceptable. Very acceptable numerical and 2D graphical optimization results using the polynomial ILS method from the HTSC Hg-cuprates molecular effect model were obtained with almost zero errors (errors about [10^{-3}, 10^{-11}], Tables 5 and 6, Intel Core-3). The simple ILS method programming for the HTSC Hg-cuprate errors were higher (errors about [10^{-2}, 10^{-3}], Table 4).

In brief, the GA and 3D/4D interior optimization methods have verified previous studies using the 3D/4D interior optimization methods for chrome [2–4]. The GA method is proven as acceptable/accurate (errors about [10^{-6}, 10^{-7}], Table 2, Intel Core-3); the method is in parallel with the 3D/4D interior optimization method. A primary hypothesis for HTSC was tested with the Hg-cuprates group. Both the numerical and graphical results are very acceptable. However, the extension of this molecular effect model to several groups of HTSC remains to be demonstrated.

6. Scientific Ethics Standards

The advances in Interior Optimization and Graphical Optimization were created by Dr Francisco Casesnoves on 15 March 2022. The basic 2D/3D graphical optimization methods were created by Dr. Francisco Casesnoves on 3 November 2016, and the interior optimization methods in 2019. The 4D graphical and interior optimization methods were created by Dr. Francisco Casesnoves in 2020. This new GA software was originally developed by the author. This article contains information about previous papers, whose inclusion is essential to make the contribution understandable. The GA nonlinear optimization software was invented/improved based on previous contributions to subroutine modifications, patterns, loops, graphics, and optimal visualizations. In the Introduction section, the paragraph on the basic Tikhonov functional parameters was taken from [11]. The 4D interior optimization method is originally from the author (August 2021). In general, all engineering software constitutes advances/improvements from author's series publications [2–4,12–15,19–27]. This study was carried out and the contents were investigated according to European Union Technology and Science Ethics standards in the *European Textbook on Ethics in Research* from the European Commission, Directorate General for Research, Unit L3, Governance and Ethics, European Research Area, Science and Society, EUR 24452 EN [45–47], which was based on *The European Code of Conduct for Research Integrity*, revised edition, ALLEA, 2017. This research was conducted entirely by the author, including the computational software used, calculations, images, mathematical propositions and statements, reference citations, and text. When a mathematical statement, proposition, or theorem is presented, a demonstration is always included. If any numerical inconsistency is determined after publication, the corresponding explanations/corrections are included in subsequent articles/books. The article is exclusively scientific, without any commercial, institutional, academic, religious, religious-similar, non-scientific theories, personal opinions, lobbies influences, friens, colleagues or relatives favours, political ideas, or economical influences. When anything is taken from a source, it is adequately recognized. Ideas and some text expressions/sentences from previous publications were emphasized with the aim of clarification [45–47].

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standards

Review

The Linguistic Challenge for Standards

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Abstract: Standards serve a valuable function that enable efficiencies, technological advancement, and commerce. To date, there is little examination of the problems with standards, their implementations, and methodologies that could be introduced to improve utility and utilization. This is contrasted against the large inventory of standards that exist, and proliferation of standards. More available literature exists on standards wars that focus on attempts at market dominance, persistence of 'legacy' standards in light of newer and 'better' solutions, cases for and against multiple standards, and even legal cases regarding anti-competitive behavior leveraging dominance in particular standards. This, however, focuses more on the politics as opposed to presenting a more fundamental examination of the cause for the existing friction. Through applied linguistics, it becomes more apparent that differences in language, using Communities of Practice as a guide, can provide a dimension to standards development and implementation. Friction in standards arises when standards are viewed as broad and universally applicable versus being the expression of a specific Community of Practice, and therefore should be specifically and formally scoped using linguistic methods.

Keywords: applied linguistics; linguistics; standards; standards development; expert bias; communities of practice

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1. Introduction

Peter Glavič states in his introduction to the Standards journal that standards can be international, national, regional or corporate [1]. The variety and sheer number of standards would seem counter-intuitive, as Glavič continues later, "In spite of the great number of different standards, new ones are appearing daily."

New standards are developed to address new areas of interest, such as those being created to address things as varied as COVID-19 to climate change. Yet, new standards also are created for things that already have standards for them—from identifiers to processes to measurements.

This results in friction in multiple ways. Standards organizations may appear to compete with each other to prove that the standard they back is the better or more 'correct' standard. Individual participants have conflicts in the standards development process on if a new standard is actually needed or not. Users are conflicted on if one standard or the other is the better choice. Companies spend significant money and risk in backing one standard over another, from everyday decisions in using Apple over Android platforms, to more field-specific issues such as utilizing ISO15022 messaging standards or FIX Protocol standards within international financial services communications.

Indeed, this challenge is highlighted in many of the first papers for this Journal. In "Current Ice Adhesion Testing Methods and the Need for a Standard: A Concise Review," [2] the researchers highlight how different tests for ice adhesion produce different, and sometimes conflicting results based on different base conditions and variables. Using this as a basis, they offer yet another method for testing. In "The Need to Accurately Define and Measure the Properties of Particles" [3], the researchers illustrate the difficulty of particle measurement and that at least seven different methods exist to account for different variables. Additionally, "Review of the International Systems of Quantities and Units Usage" [4] specifically illustrates different measurement systems, their origins based in different languages and cultures, and the difficulties in gaining adoption for a new standard for measurements.

In all these papers, as with standards themselves, the specific problem is defined well, and how the standard addresses that problem is typically well scoped in regard to function. However, the user community—that is the specific group the standard is meant to be used by in practice—is not well defined or addressed. Standards are created with the intention of being used for particular purposes; in expressing values or results in a consistent and sharable manner, to encode a consistent process that will produce repeatable results, or to establish best practices in a particular discipline. The target user community that a given standard is meant to provide these benefits to, however, is given passing mention, if at all. Many times, it is inferred or loosely defined using generic language that encompasses a larger community than perhaps the standard applies.

Language is the basis of how we communicate, and is informed mostly by the speech community an individual belongs to. While speech communities that are closely related or interact often may share some commonalities, their individual language varieties do differ, sometimes in dialect or jargon, but possibly more severely. This necessarily requires translation and interpretation to link similar concepts and convey intended meaning.

Hockett's (1960) [5] 13 original "Design Features of Language" include arbitrariness, which in simple terms states that there is no connection between the logical meaning of a word and the sound form (signal) used to express it. There is nothing about the word "book" that links it intrinsically or logically to the object that we know to be a book. It could easily have been called "house". Further, the feature of traditional (or cultural) transmission supports that language is learned through social interaction, linking our learned language with the community in which we learn it.

The determination of language varieties itself can be arbitrary, whether something is considered a 'standard' dialect of a language, a language unto itself, or determining if a field specific language is considered jargon or a lexicon belonging to a community of practice due to the language's practice-specific nature. Language used by the medical profession, by engineers, by particle physicists all are specialized and typically not intelligible to the lay person, or other groups. Additionally, even within one group, such as engineers, the language used by civil engineers can differ greatly from that of electrical engineers.

Another key aspect of language is that it is always changing. John Lyons (1968) [6] calls for recognition of "the various functions a language is called upon to fulfill in the society which uses it" in regard to language change. Within specific communities performing a shared function, then, one could expect to see specialization of language in order to support the more efficient sharing of information. Therefore, between the arbitrary nature of language, the social learning of language, and the tendency of language to change to suit the needs of the group needs it, it can indicate that specific communities that have a shared function and culture also will evolve their own language. Whether one wishes to label that a dialect, jargon, or otherwise is itself arbitrary to the point that the meaning being conveyed by that group is specific to that group's knowledge.

This interacts with standards, as standards are most often created by a specific community that shares a particular purpose or function, and hence communicates with a specific language. This community therefore can be expressed as a form of speech community defined as a Community of Practice. Within sociolinguistics, there are multiple definitions of a "speech community" that vary according to competing theories on what qualities should be included. Differentiation typically is based upon using only linguistic characteristics to define any speech community aligning with Chomsky's hypothesis of a "completely homogeneous speech-community" [7], versus including social aspects, such as Hymes (1974) [8], who forwards that speech communities cannot be defined solely through linguistic criteria, or Wardhaugh (2006) [9] who defines a speech community as "a social group with members having similar/coherent speech characteristics".

The purpose of this paper is not to debate these differences, but to utilize the concept that is used as a foundation by sociolinguistics and applied linguistics in regard to defining

Communities of Practice. Lyons (1970), in line with Chomsky, defines a 'real' speech community as "all the people who use a given language (or dialect)." Meanwhile Hockett (1958) offers a more expansive view as "the whole set of people who communicate with each other, either directly or indirectly, via the common language".

Criticism of the more strict definition by Lyon comes in that "if speech communities are defined solely by their linguistic characteristics, we must acknowledge the inherent circularity of any such definition in that language itself is a communal possession". (Wardhaugh) Wardhaugh's views are less in conflict with Hockett, in that Hockett leaves open the classification of what qualifies as a "whole set of people," as a "social group" certainly qualifies as a "whole set of people".

The difficulty comes in defining this "social group" or "whole set of people". Wardhaugh (pg 119) notes that Hudson (1996) rejects the view that it is simple to use the concept of the speech community without difficult: "our sociolinguistic world is not organized in terms of objective 'speech communities' even though we like to think subjectively in terms of communities or social types, even as 'Londoner' and 'American'." Further, a single individual does not define, and is not defined by their speech community, as any individual may belong to multiple speech communities by nature of multilingualism.

As such, it is acknowledged that a "'group' is a difficult concept to define" and thus also makes the 'speech community' "a very abstract concept." (Wardhaugh). This is where the introduction of communities of practice provide some assistance, especially in relation to creation, definition, and implementation of standards.

Wegner-Traynor defines a Community of Practice as "a group of people who share a concern or a passion for something they do, and learn how to do it better as they interact regularly" [10]. While this is very broad, Wegner-Treynor state that the key elements in bounding a community of practice are the domain, the community, and the practice. Members are brought together by a learning need they share (the domain), this collective learning becomes a bond over time (community) and their interactions produce resources that affect their actions (the practice).

Standards are affected by the language of the community, informed by the culture, processes and functions they perform. The question should be asked if those creating any standard are a proper representation of the community in which the standard is intended. Care should be taken to determine how broad the community is being defined.

It should not be assumed that by virtue of using the same human language (i.e., all are speaking English) that the same functional language (that of the target speech community, community of practice or domain) is being spoken and all involved belong to the same Community of Practice. This is one of the missing elements in the standard process, from creation of standards to evaluation of a standard for use, to final implementation of standards.

The purpose of this paper is to highlight the linguistic variation not formally included in the standards process, implications and misunderstandings that result, and benefits of introducing an applied linguistic component, specifically the formal inclusions of communities of practice as a bounding mechanism, to the standards process.

2. Applied Linguistics and Communities of Practice

Standards are well defined solutions for specific problems, meant to bring single unity and consistency where diversity may exist. Yet, by virtue of being branded a "standard" the specific problem the standard was created for is many times lost or ignored in pursuit of expanding the application and use of said standard, beyond the original community and use case. This, ironically, works against the core purpose of what a standard is. This issue is most apparent in standards focused on data, messaging, and interoperability. While you may have misapplication of a physical standard, such as a type of screw, the lack of arbitrariness in physical objects makes this less likely. Thread design on a screw impacts use in different materials, such as wood or metal, and there is less interpretation involved.

One may “mis-use” a screw with a thread type for wood in metal, but the mismatch is apparent in physical form.

However, data, messaging and related interoperability standards, language comes to the forefront. By their very nature, these types of standards are focused on communication using language. Additionally, given the effort necessary to create standards, wide applicability is typically sought after.

The language paradox is that language is meant to enable communication, yet language is constantly changing and evolving; therefore, impeding clear communication. Language change, led by dialects and jargon, enables better communication within a single group. However, in doing so, that language will diverge away from related communities. Standards can be viewed as an expression of language of a specific community and act in the same way. Standards enable better results within a targeted community and use case. Yet, in implementation, this nuance is lost when the standard is pushed as a common language solution for all communities in a social system.

This can primarily be attributed to the lack of formal definitions of the Community of Practice (or ‘domain’) any standard is created for. In the formulation of a standard, the Community of Practice is not precisely defined because the community or domain is assumed or inferred by the structure of the organization and participants creating the standard. Indeed, the community creating the standard is self-selecting, and assumes such of any wider audience. General terms that leave much to interpretation are used to define the target community. Some examples are ‘financial services’, ’teachers’, or ‘doctors’.

While these classifications might not appear problematic, one could challenge that ‘teacher’ could refer to elementary educators or university professors. Further, one could challenge what education levels ‘elementary educator’ encompasses. It should be understandable that standards for ‘teachers’ that are applicable to higher level education would likely not be appropriate for elementary education, and visa versa.

Even for a ‘hard’ science like mathematics, there can be wide variations of understanding and implementation, such as the difference between mathematical physics versus theoretical physics. The point being that a speaker may know what they intend when saying “math” or “teacher”, the listener being from a different Community of Practice may have a different interpretation of what is assumed to be a clear concept.

In ISO, for example, Technical Committees are created around topics or scope, such as TC68 for “Financial Services”, TC322 for “Sustainable Finance” or TC321 for “Transaction Assurance in E-commerce”. Yet, there is little rigor in formally defining what these ‘domains’ actually encompass. TC68 ostensibly covers “banking, securities and other financial services” [11]. This is overly broad and not clearly defined. This is easily evidenced by the existence of TC322; whereas “other financial services” of TC68 can reasonably be assumed to include sustainable finance, as well as the area of e-commerce that is the subject domain of TC321.

In some cases, standardization comes from a community seeking legitimacy for their divergence from existing practices, or using standardization as a tool of power in much the same way language standardization, whether German requirements in Czech areas during the Habsburg Empire (Schjere, R. R.) [12], attempts to rescue proper English from the Americans (Mencken, 1919) [13], or disenfranchise Spanish speakers in American public services through English requirements (Hall, Smith, Wicaksono [14]). This may be intentional attempts at establishing power, or attempts to solve real problems with good intentions. However, both would seem to come from a lack of perspective or understanding of different communities of practice with different or changing language needs.

This lack of domain—or more formally, Community of Practice—definition helps illustrate what the linguistic challenge in standards is. There is a need for a formal linguistic-based methodology for defining the community any standard is for, and an evaluation of the community of experts that are defining that standard.

Both aspects are required because there can be an obvious disconnect when the community of experts who may be defining a standard may not truly represent the target community. Misunderstanding and conflicts arise between communities of practice in the standards creation and implementation perhaps because there is a lack of recognition that two practitioners are from different communities, using different language, and discourse is focused on consent rather than acceptance and recognition of differences.

This is not limited to ISO, of course. This issue exists across the standards landscape. It is part of the nature of how SSO's are structured, the composition of their membership, and the inherent expert bias and experience bias of the participants. This is not meant as an indictment, but purely a reality as a result of the function of organizations in general.

Language possesses a number of properties, 5 of which are most relevant here;

- Communities of Practice (CoP) are groups defined by a shared culture (community), shared functions (domain of purpose), and shared processes (practices) that result in a distinct and unique language unto themselves (inclusive of dialect and jargon divergences) (see Wegner-Treynor, above)
- Language is constantly evolving and is dependent on change and diversification
- There is no 'right' or 'wrong' language
- Language exists in a multitude of forms (such that the meaning of any single word may differ depending on use and context per Wittgenstein's use theory of meaning [15])
- Language is a social construct that exists in a social system

Bias is a key aspect of standards participation. It is understandable that a participant in any community instinctively knows what community they belong to, and therefore sees no need to define that community when interacting with other members. However, CoPs are not mutually exclusive, and participants may incorrectly assume a wider or smaller scope of the target community without proper discourse.

Communities of Practice will exist as individual parts in a social system of a larger construct, which can create confusion. We can imagine the human body as an overall social system that operates as a Community of Practice as a whole. However, each organ and system within the human body is itself akin to individual Communities of Practice, each performing a specific function, with its own processes.

For example, the function, and processes that define the gastrointestinal system are clearly distinct from the brain's function and processes. While they share a part in the overall goal of operating the body, they remain independent, though interdependent, entities.

Expert bias will lead participants to falsely assume that other participants are interpreting their expression in one way as opposed to potentially being misunderstood in translation to the listener's different perspective. These misunderstandings may not be discovered until much later, if at all, meaning that the foundational assumptions that any conclusions are based on are faulty.

Even within the same language there is a need to better define the Community of Practice as it relates to dialect and jargon which will impact understanding. Two English speakers will have different interpretations of the word "jumper" without discovering where one is referring to a warm sweater while the other is speaking of a baby's clothing. In creating a standard for a "jumper" this will naturally lead to misunderstandings and vastly different opinions on what the standard should include. While this example may seem somewhat pedestrian, it illustrates how a fairly simple dialect difference can cause wide variation across two associated dialects due to the CoP specific nature of language.

When approaching much more complex concepts that require higher level of expert knowledge, it can be expected that expert bias will play a larger role in misunderstanding. Due to expert bias, two experts from related but different CoPs will typically assume their interpretation is shared by other experts. Two experts from 'financial services' discussing 'payments' will have vastly different needs and goals when one is an expert in retail and consumer type payments versus the other being involved in institution and corporate payments. In the same vein, pediatricians and oncologists—both medical professionals—have fairly different areas of expertise and need, and any specific standards for either CoP are likely to be less useful for the other. However, it should be stated that the CoP specific standard has high value for the CoP it is meant for.

The aspect of language that creates frictions between CoPs is that of language change. Even in a wider social system, language within the constituent CoPs will continue to evolve and change without regard to the larger social system they belong to. In creation of standards, this can lead to development of 'shared' standards that will not be properly functional for multiple CoPs in the long term, even if tacit agreement is reached during the standardization process.

In applied linguistics, two functions enable the correction and translation of language between speech communities. Repair is the process where two speakers discover a language problem and actively seek to resolve this. In the case of the "jumper" previously, after some discourse, one speaker will discover through other clues that their interpretation of "jumper" differs. This will likely occur when trying to standardize the number of limbs to be covered or length requirements. A resulting conversation will then be a process of corrective action to explain the details that are different in the two language interpretations.

Accommodation is a function where one speaker accepts the second speaker's expression, even though it is not native to them, and proceeds to use the opposing language to enable communication. Thus, they 'accommodate' the non-native language and translates internally. These are both very simplistic explanations of two aspects of discourse, but are useful to look at differences in language between communities of practice without delving too deep into pragmatics (Austin, 1962).

The concept of meaning in context (i.e., pragmatics) is relevant to discussion of language variety between communities, as the community of practice itself is one of the variables in providing context and intention in meaning. In financial services, the context when discussing a 'trade' from a front office community (trader on an exchange) speaks to the execution on an exchange. Meanwhile the context from an operations community in regard to the utterance 'trade' would indicate a transaction being settled at a local depository. These are two distinct objects with only the most tenuous of connecting relationships in meaning, as will be explored further below.

Where two different CoPs sharing a social system work on a standard, the tendency for one or both will be to repair or accommodate the other. The resulting standard, then, becomes an agreement on an interpretation that is not offensive to either CoP, but in most cases does not capture the nuance of either. This 'agreed' meaning does not correspond to the actual language meaning of either CoP and will have less utility. Said another way, "Consensus is agreement, nothing more. It provides no assurance of accuracy, correctness or feasibility. It's only a valid decision-making process if agreement is more important than results" [16].

In complex problems which standards aim to address, consensus many times can be a poor approach, as alternatives and viewpoints are bypassed. Harvard Business School Professor Len Schlesinger states "They get to convergence much too quickly, which is largely one of the most negative byproducts of the consensus-oriented model and why it's only appropriate for the most simplistic, best-structured decisions" [17].

The resulting consensus meaning will not correspond specifically to the function, nor processes, of either CoP, without added clarification. Any additional CoP specific nuance added to the agreed definition immediately changes the original agreed meaning such that language once again diverges between the CoPs, invalidating the standard itself.

For example, two financial services experts working on a data definition standard to define "trade" agree upon "a trade is an exchange of an asset for some other asset between two parties". However, the experts belong to two distinct CoPs, such as front office and clearing operations, as in the example provided previously.

Within the front office, the data standard is used to describe executions that take place on an exchange. To make the standard usable, the definition within the front office CoP evolves to include the existence of an exchange. Yet, within the clearing operations, 'trade' is deemed specific to indicate the trade that settles in the market for an investment manager taking a position in some asset. In the clearing CoP, then, exchange is not an included aspect, but instead the general market jurisdiction becomes a mandatory aspect.

While the standard ostensibly describes the same thing—an asset being exchanged between two parties—the reality is that the two instances are fundamentally different and not interchangeable instances. The standard meant to solve for a problem may only solve for a short period, as a result, until the CoPs diverge naturally again. "Problems never stay solved because of constantly changing contexts" [18].

The function for which it is being used, and the processes in which the definition is being applied are distinctly different (context). Without the nuance provided by expert knowledge, the standard definition itself does not provide value in regard to solving any specific need or requirement. Within each CoP, the definition language evolves and diverges as need and context requires, without any change to the actual standard. Further complexity can be introduced when a third CoP comes in, such as a regulator, and expects to use the standard for "trade" as a requirement for what needs to be reported.

In financial services standards, the concepts of "payment" and "trade" are just two examples where multiple definitions exist, based on community and context. Within data and messaging standards such as ISO20022, or FIX Protocol, definitions based on context and community of practice are not defined. Multiple definition versions exist in ISO20022 for example, corresponding to the language variety of any one submitting organization into the dictionary.

However, context and community are not included as classifiers within the dictionary, leaving listeners to try and determine which definition may be the one being expressed in any communication.

This brings us to the language property that there is no 'right' or 'wrong' language. Both definitions, specific to each CoP are correct. To better enable communication between CoPs with standards, both definitions should be standardized specific to each CoP, therefor ensuring the context within the community is properly attributed. Each specific standard should be further qualified with a formal definition of the CoP it specifically applies to, as the meaning in context can vary according to the community and use. This then offers the ability to create a standard process that can translate between the definitions and identify the different nuances and missing elements that are required to effectively resolve the difference and provide clear meaning. Thus when the third CoP enters, they are able to properly translate the different meanings, based on the context defined within each specific CoP. The goal is enabling proper understanding during communication between CoPs while preserving functionality necessary within the individual CoPs.

3. Applying CoPs in Standards

This is not to say that all standards that exist without proper CoP attribution are problematic. As noted, standards for physical objects will naturally have less language and community of practice related ambiguity. However, all standards would present more utility, and clarity, if the exercise was undertaken to formally define the target CoP any standard should apply to, and within what context. Where more than one CoP is identified, this would highlight where accommodations were made and that further work to more precisely define the standard may be needed to account for differences in interpretation that would result in different results or implementations based on CoP. This may result in two different, if similar, standards that are more informative and appropriate for use.

A pitfall for standards many times comes not during the standardization process, but after. When a standard exists, there are two potential pitfalls. First is the experts and standard organization that produced the standard seek to promote its use beyond what the original scope may have been. Second, when in search of a solution, many times a standard that seems 'close enough' is chosen with the assumption that the alternatives (creating a new solution or validating ad hoc solutions that exist) are either more difficult, or do not have the political support that a solution carrying the label of 'official standard' carries.

The root of the problem may partially exist with the use of the word "standard" itself without qualification of what and who the standard is for. The accepted definitions of "standard" speak to something that is "regularly and widely used" [19], "something established ... as a model", and exhibiting "a level of quality" [20]. There is then an assumption that in choosing a "standard" that the choice will experience less friction or resistance, with the onus on those arguing against the standard.

The problem of implementing standards, especially standards focused on interoperability, is not a new phenomenon. Egyedi and Dahanayake, in "Difficulties Implementing Standards" [21] allude to the problem of multiple CoPs as an issue; "The ideal of democratic, consensus-oriented decision making more or less solicits political compromises in committee standardisation. This can result in a standard which includes several options, or in intentional vagueness in the way a standard is formulated so that opposing parties can rally behind it)".

In regard to implementation, Egyedi and Dahanayake observe: "Indeed, such outcomes are a natural consequence of the formal standards bodies' past emphasis on their guardianship of the quality of the standards process (voluntary consensus process), rather than on features of the standard or on standards implementability". Indicating that implementation is not a concern during the standards creation process, but only that a proper consensus process has been followed such that the standard will be amenable to as wide an audience as possible.

Egyedi and Dahanayake therefore promote that idea that standards include implementation-specific details. Though they do not expand further on what would be needed to create the context specific to implementation details. Matthew J. Everett notes "Developing standards and test requirements is difficult, as it involves coming to consensus with a group of people with different backgrounds, interests, and motivations. It is essential that standardization groups begin with a clear agreement on the purpose of whatever they are developing" [22]. Here, is where the introduction of the CoP the standard is meant for, and for what purpose would begin to provide fruit. At the same time, participants need to be aware to not confuse the community of standards practitioners with the target community of practice a standard is being developed for.

The ambiguity created by implementation-agnostic standards works against what standards are meant to achieve. The desire to include as many perspectives as possible to ensure rigor in any standard in many ways works against the end goal by pitting experts against experts without the guiding principle of which expert community the standard should satisfy. Expert bias results in the political process of consensus unintentionally generating ambiguity in lieu of one set of experts deferring to another, which is a common issue with collective decision making. Experts will commonly extend their opinion beyond their core area of their expertise when involved in collective decision making. When experts from multiple Communities of Practice are involved in a collective decision making process where only one group has the core expertise, the irony is the experts that should be deferred to are in the minority and overruled.

Therefore, the research and literature available around the problem with standards is lacking, though in what is available, there is a common theme regarding the lack of clear agreement on context that surrounds the purpose and intent of any standard. Additionally, while potential remedies have pointed to providing those aspects, no formal methodology for doing so is proposed.

Although better defining groups through communities of practice may seem a linguistically arbitrary designation, it can provide a counterbalance to the consensus process where all context is removed, unintentionally or not. As with the examples in ISO20022, providing a simple dictionary with no language context that a community of practice designation can provide leads to ambiguity resulting in misunderstanding and errors. As there is no framework for defining context and community, there is no discourse that can take place to repair language error in these data standards.

4. Conclusions

To date, there is little examination of the problems with standards, their implementations, and methodologies that could be introduced to improve utility and utilization. This is contrasted against the large inventory of standards that exist, and the more available literature on standards wars that focus on attempts at market dominance, persistence of ‘legacy’ standards in light of newer and ‘better’ solutions, cases for and against multiple standards [23], and even legal cases [24,25] regarding anti-competitive behavior leveraging dominance in particular standards.

If we consider standards an expression of language, however, there is a potential path towards a formal, though still subjective, methodology to examining, evaluating, and developing standards through an applied linguistics lens. In human language, the control and imposition of language has been and continues to be used as a political tool [26]. This aligns with the issues seen within the standards world.

There are competing goals. There is the desire to simplify complex problems across a broad population without breaking down into component parts. A semi-democratic consensus process is used to resolve the inherent political aims of potentially dominant individuals or companies in any standardization process. The need to interoperate and communicate across different groups, with different goals, but that need to work together within a larger social system create issues in the collective decision making process with multiple experts involved. Finally, standards setting organizations themselves desire relevance through the promulgation and use of their standards, without regard to implementation or appropriateness based on formal use case analysis.

Many facades are created to provide an illusion of standardization. The use of English and French as required language for standard document publication simplifies drafting and publishing but ignores the fact that non-speakers still translate those back into their own native language. The lack of implementation considerations, or formal definition of the community the standard is for, results in use of a standard as a solution for things it was not intended. The impact is that the standard is misinterpreted and the solution does not conform to the intent of the standard, degrading and diverging the standard from its specified definition and purpose.

There is no question that standards provide significant value to the world and create a foundation for rapid advancement of knowledge and technology. However, in the pursuit of standards, the very important step of defining the community the standard is for, and the specific use and implementation goes ignored.

Diversity is important, but it should not be at the cost of greater authority provided to those that are not experts in the community the standard is meant for. Nor should one community expect to define another community. Understanding of other communities must come from interaction and discourse prior to development of any standard. Broad classification serves to only ignore important nuances—and results in a lack of rigor in exposing foundation level misunderstandings or differences in perspectives.

The literature on why we have these problems with standards is admittedly bare. We can look to behavior, culture, and humanistic tendencies such as politics as the main culprits—all aspects not examined in standards. There are policies and procedures that attempt to mitigate these forces in different SSO’s, but they do not directly address identifying and resolving them.

Additionally, someone will always find a “better” way to do something, which will lead to a new standard. If there is not full agreement that this new standard should be used and all others be abandoned, divergence will occur—much like language itself.

The reality is that most new standards offering a better solution provide a better solution for a particular community. However, without this formally captured, properly identified, and continuously revisited and revised, the “problem” with multiple standards “for the same thing” will continue to persist, standards will be misused and diverge from their primary intent, and the politics of control through standards endorsement and abuse will continue.

Use of an applied linguistics methodology can provide a significant boost to the standards process. Clearly identifying and documenting the CoPs involved in a standard development not only gives clarity to later implementation and use case, but it can formally expose potential political, cultural, and behavioral conflicts through an agnostic process. Formally understanding the CoP or CoPs that are the target community for the standard also can highlight where expertise may be lacking, or counter expert bias.

The end goal is to provide a method, through applied linguistics, to understand and resolve issues regarding seemingly duplicative standards, prevent the misapplication and 'scope creep' of standards, and create a better overall development process through a formal definition of community, context, and use case.

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