systems

Systems Thinking

Edited by
Cliff Whitcomb, Heidi Davidz and Stefan Groesser

Printed Edition of the Special Issue Published in *Systems*

www.mdpi.com/journal/systems

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This is a reprint of articles from the Special Issue published online in the open access journal *Systems* (ISSN 2079-8954) (available at: https://www.mdpi.com/journal/systems/special_issues/system_thinking).

For citation purposes, cite each article independently as indicated on the article page online and as indicated below:

LastName, A.A.; LastName, B.B.; LastName, C.C. Article Title. *Journal Name* **Year**, *Article Number*, Page Range.

ISBN 978-3-03936-796-2 (Hbk)
ISBN 978-3-03936-797-9 (PDF)

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About the Editors

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Heidi Davidz is a Principal Engineer in Systems Engineering at Aerojet Rocketdyne (AR), where she leads Digital Engineering and Model-Based Systems Engineering. Her previous roles include SE Discipline Lead; Chief Process SE; Stennis Space Center Achieving Competitive Excellence Manager; RS-68 Test Conductor; and Systems Development, Verification, and Test Engineer. While at Aerospace Corporation, she provided support for NASA Headquarters and National Security Space projects. She completed her Ph.D. in the Engineering Systems Division at the Massachusetts Institute of Technology. While at GE Aircraft Engines in the Edison Engineering Development Program, she earned an M.S. in Aerospace Engineering through the GE Advanced Courses in Engineering and the University of Cincinnati. She holds a B.S. in Mechanical Engineering from The Ohio State University. Dr. Davidz was a Part Lead Author and Associate Editor for the Body of Knowledge and Curriculum to Advance Systems Engineering (BKCASE).

Stefan Groesser has been working at Bern University of Applied Sciences since 2011 and at the Department of Engineering and Information Technology since 2016. He is Dean of the Industrial Engineering division as well as the "Strategy, Technology and Innovation Management" research group. Previously, he was Professor of Strategic Management at the Business School and headed the Strategy and Simulation Labs (S-Lab). From 2015 to 2017, he was deputy head of the Institute for Corporate Development at Bern University of Applied Sciences. In addition, he was in charge of the key topic "Strategic Management, Entrepreneurship and Innovation". He has served as Deputy Head of the Bern University of Applied Sciences Flagship for Energy Storage Research since his appointment in 2016.

Preface to "Systems Thinking"

Systems thinking can be broadly considered as the activity of thinking applied in a systems context, forming a basis for fundamental approaches to multiple systems disciplines, such as systems engineering, systems science, and system dynamics. As the impact of global system interconnectivity proliferates and the complexity of human-made systems grows, the process of sense-making based on systems thinking becomes critical. This issue focuses on the nature of systems thinking as it applies to systems engineering, systems science, system dynamics, and related fields. In the twelve articles included in this Special Issue, contributors have presented approaches, models, and theoretical frameworks to deal with topics related to systems thinking for academic, disciplinary, and industrial applications.

Several articles address enhancements to systems thinking inquiry. In "Systemic Semantics: A Systems Approach to Building Ontologies and Concept Maps", a systemic and systematic framework for selecting and organizing the terminology of systemology is provided. The article shows the value in applying a systems perspective to ontology development in any discipline and provides a starting outline for an ontology of systemology.

The article "A Systematic Framework for Exploring Worldviews and Its Generalization as a Multi-Purpose Inquiry Framework" proposes a comprehensive "Worldview Inquiry Framework" that can be used across methodologies to govern the process of eliciting, documenting, and comparing the worldviews of stakeholders. This is a special case of the "General Inquiry Framework" which can be tailored for other contexts such as problem solving, product design, and fundamental research.

In "On the Architecture of Systemology and the Typology of Its Principles", an architecture for systemology is introduced, which shows how the principles of systemology arise from interdependent processes spanning multiple disciplinary fields, and on this basis, a typology is introduced, which can be used to classify systems principles and systems methods. This framework, consisting of an architecture and a typology, can be used to survey and classify the principles and methods currently in use in systemology, map vocabularies referring to them, identify key gaps, and expose opportunities for further development.

The article "Modeling Isomorphic Systems Processes Using Monterey Phoenix" describes preliminary research, as a proof of concept test, on the potential value of formalizing isomorphic systems processes (ISPs) based on systems science research using the Monterey Phoenix (MP) language, approach, and tool. It was found that using MP to formalize relationships within and among presently non-formally described ISPs yielded new insights into system processes.

"A Bibliographic and Visual Exploration of the Historic Impact of Soft Systems Methodology on Academic Research and Theory" describes a bibliometric meta-analysis of 286 relevant publications in engineering, business, and other social sciences fields. This explores the historic impacts of SSM on academic research and systems thinking in relevant publications that described or employed SSM for research during 1980–2018. Understanding the impact of SSM informs future use as a methodological approach to comprehend complex problem situations.

Other articles address systems thinking application. "Maturity Models for Systems Thinking" examines current thoughts regarding the value and pitfalls of maturity models. Principles and exemplars are identified that could guide the development of a Maturity Model of Systems Thinking Competence (MMSTC) for the varied roles people inhabit in systems contexts.

In "Systems Thinking Education—Seeing the Forest through the Trees", the development of systems thinking among engineers and engineering students is studied, including administration of a personality test for engineers with high systems thinking skills. Development of a new systems thinking study course is also presented. Engineers with certain personality traits acquire or improve their systems thinking capabilities through a gradual, long-term learning process and by acquiring the necessary tools.

Two articles address application of systems thinking to aid sustainability specifically. "Could Education for Sustainable Development Benefit from a Systems Thinking Approach?" addresses whether it could be possible to interlace education for sustainable development (ESD) and systems education to overcome the obstacles preventing the implementation of sustainability in education. The literature review identifies joint approaches to develop an instrument in the educational work toward sustainability.

In "Using Systems Thinking to Understand and Enlarge Mental Models: Helping the Transition to a Sustainable World", causal loop diagramming (CLD) is used to describe the general, prevailing citizen viewpoint and to propose a wider mental model that takes the natural world and sustainability into account. Adopting the wider mental model can help the industrialized world design better policies to achieve both national and United Nations (UN) sustainable development goals.

A related article, "Natural Systems Thinking and the Human Family", describes the human family system as a network of relationships, linking each family member to every other, responding dynamically to its environment and the conditions to which all members must adapt. Complex development of the human brain appears to have co-evolved with the interactional processes of the family. An integrative theory of human behavior offers broader explanatory and investigative pathways for understanding human activity.

In "A Systems Thinking Approach to Designing Clinical Models and Healthcare Services", systems thinking is used as an alternative strategy to designing clinical system models and healthcare services to alleviate many of the current design challenges in designing integrated services for chronic conditions. An illustrative example taking a clinical model and describing it as a system model is presented.

As another example of industrial application of systems thinking, "Conceptualizing Shadow IT Integration Drawbacks from a Systemic Viewpoint" introduces a systemic viewpoint to the research on Shadow IT. Business units can implement Shadow IT (SIT) without involving central IT. The article provides a conceptual framework for SIT integration drawbacks which classifies the drawbacks into three dimensions for practitioner use.

The breadth of topics for this issue is wide, and the common theme throughout is using systems thinking to aid sense-making for human endeavors. From theoretical frameworks to specific applications, the articles describe deep analysis and thought-provoking ideas. As product complexity escalates and interconnectivity of the human experience swells, the importance of systems thinking is apparent. We hope you enjoy this issue.

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Article

A Systems Thinking Approach to Designing Clinical Models and Healthcare Services

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Received: 29 October 2018; Accepted: 14 March 2019; Published: 24 March 2019

Abstract: Chronic diseases are on the rise, increasing in number and treatment regimen complexity. Consequently, the needs of patients with chronic diseases are increasing and becoming more complex and multi-faceted. Such chronic conditions require addressing not only the physical body, but also psychosocial and spiritual health. The healthcare delivery system, however, organically organized into departments based on physical organ systems. Such a configuration makes it ill-suited to provide comprehensive multi-faceted healthcare services that span multiple departments and specialties (e.g., podiatry and endocrinology for diabetes; primary care and psychiatry for behavioral health; and palliative care physicians, chaplains, and social workers for end-of-life care). To deliver new services, the medical field typically designs new clinical models to base its new services on. Several challenges arise from typical approaches to designing healthcare services and clinical models, including addressing only single conditions, describing models only at a high-level of abstraction, and using primarily narrative documents called text-based toolkits for implementation. This paper presents and uses systems thinking as an alternative strategy to designing clinical system models and healthcare services to alleviate many of the current design challenges in designing integrated services for chronic conditions. An illustrative example taking a clinical model and describing it as a system model is presented.

Keywords: systems thinking; systems engineering; healthcare system design; clinical models; socio-technical system; model-based systems engineering

1. Introduction

Growing healthcare costs have drawn significant attention to the healthcare delivery system and its fragile and fragmented nature [1]. Similarly, the growing burden of illness and its impact on individuals, families, and society has led to a concerted effort towards addressing the needs of patients (i.e., focusing on person-centered care). The consequences of the growing burden of illness compounded by an increasingly expensive healthcare delivery system place grave consequences on our economy and way of life.

National Academy of Medicine Reports continue to highlight the need to improve healthcare delivery [2,3]. This includes designing healthcare systems that address current needs of patients and can be implemented and disseminated across varying healthcare system environments.

1.1. The Changing Needs of Patients: From Treating Acute to Chronic Conditions

Acute conditions, namely infectious diseases and traumatic injury, dominated the medical problems of the 19th and early 20th century. In response, the development of the biomedical model addressed these problems by focusing on the body as a machine [4] and therefore disease as the consequence of breakdown in the machine. This reductionist approach to the physical body analogy led to dividing the healthcare delivery system into departments based on discrete service types (e.g., cardiology, endocrinology, podiatry).

Healthcare needs have significantly shifted from treating primarily acute conditions to treating primarily chronic conditions. Chronic conditions now make up over 78% of total healthcare costs in the United States [5]. Furthermore, expenditures for patients with multiple chronic conditions are up to seven times as much as patients with only one chronic condition [6]. This is a significant population given that over half (51.7%) of all Americans have at least one chronic condition and almost one third (31.5%) of all Americans have multiple chronic conditions [7]. This problem increases dramatically with age where almost half (50%) of all people aged 45–64, and 80% of those 65 and over, have multiple chronic conditions [7].

While chronic conditions are typically described by their long-term disease duration [8–11], the complexity that arises from the condition is not to be underestimated. Chronic conditions are particularly complex in that they tend to involve multiple factors with multiple interactions between them [12]. These conditions are described as having a complex, multiple, and co-occurring nature. These conditions can be primarily physical (e.g., diabetes and obesity), physical and behavioral (e.g., cancer and depression), or mental and behavioral (e.g., substance use and mental health).

Increasing patient needs associated with chronic conditions have led many healthcare systems—motivated by both cost and quality—to focus on providing holistic care. Studies have shown improvement in patient health outcomes and reduced system costs when services are restructured to focus on patient-oriented experiences and needs [13,14]. The recognition of such improvements has led to an increasing interest in providing single-point services, classically provided by different departments or healthcare delivery systems (e.g., primary care and behavioral health, palliative care and cancer).

1.2. The Current Healthcare Delivery System and Challenges of Conventional Clinical Modeling

The healthcare delivery system organically developed to address acute conditions. The characteristics of chronic conditions present several new healthcare delivery challenges [15,16]. Namely, continuing to deliver care well after the individual has left the healthcare facility, deeply understanding the health state of the individual, managing individualized health outcomes, and coordinating numerous practitioners representing many medical specialties [15].

Now that healthcare systems recognize the need to provide services tailored to patients with chronic diseases, healthcare uses classic clinical constructs typically used in medicine to design such services. Current clinical methods and tools to generate evidence-based models and implementing them present five key challenges. These challenges have been identified by the author based on the literature, discussions with many different types of clinicians from different training backgrounds (e.g., physicians, nurses, medical assistants, etc.) and specialities (e.g., primary care, psychiatry, palliative care, emergency medicine, etc.). These challenges are presented in Table 1 and described in detail below.

Table 1. Challenges in designing clinical models.

Challenge 1:	Designed based on **single-diagnosis**. Generally, not applicable to patients with multiple conditions,
Challenge 2:	Described at a **high-level of abstraction** with a focus on human personnel,
Challenge 3:	Described using **text-based** toolkits with minimal visuals,
Challenge 4:	Described with expected paths; **qualitatively** describes the system and may be biased, and
Challenge 5:	Described with minimal to **no specificity of implementation-level details.**

Challenge 1: Clinical models are typically designed based on a single-diagnoses. The medical approach for generating evidence-based models, treatments, and protocols rests on the current gold standard of testing them using randomized clinical trials (RCTs). RCTs have very strict inclusion criteria, meaning that they test using a homogeneous cohort of patients. Consequently, patients with multiple and complex conditions are specifically excluded, leading to limited generalizability for patients with multiple or complex conditions.

Challenge 2: Clinical models are typically described at a high-level of abstraction with a focus on personnel (i.e., human personnel are one type of resource in the healthcare system). In doing so, clinical models do not define the needed functions, but instead describe the type of provider that should be performing these functions. Describing the model based on the type of provider is problematic for three reasons.

First, identifying a function based on the type of provider is no longer as informative as it used to be. Typically, clinical medicine names the type of provider in a manner that alludes to their functions (e.g., a surgeon performs surgery). This was possible because classic Doctor of Medicine (MD) education, training, and certification processes provide a clear description of scope of work for such a personnel. There are now many additional trainings, certifications, licenses, and bodies of knowledge that are not encompassed in the classic training and medical degree (e.g., providing palliative care, providing behavioral health care, providing opioid treatments). There is also a critical phenomenon occurring in medicine. Some of the fastest growing resources in healthcare are non-MD personnel [17]. While many of these non-MD clinicians (e.g., nurses, medical assistants, behavioral specialists, social workers) also have education programs and certifications, their experiences and continued training allow them to practice with a wider scope of work and provide higher levels of clinical care. For example, using the term "nurse" only describes the most minimal functions that a nurse can provide based on a nursing degree. However, there are nurses that provide specialized nursing support for complex palliative care, complex medication management, opioid treatment, and addiction recovery, to name a few.

Second, new integrated services may bring together personnel from across-departments, but it is important to understand that they tend to bring significantly different clinical language, culture, and operational practices. Not specifically addressing scope of work or tasks of each personnel introduces many possibilities for misunderstanding and allows the behavioral dynamics of the team to be reduced to individual personalities. Bringing together human resources from different departments or systems requires the explicit description of not only individual scope of work, but also dyads and the aggregate team scope of work.

Third, some integrated services may describe individual resource functions or tasks, but functions performed by multiple resources are rarely specifically described as to when, how, and where they are to occur. Furthermore, key functions required for team success are not well defined and, if defined, not allocated the appropriate value (i.e., value in terms of time to perform a task or payment for a task). For example, curbside consults (i.e., when a treating physician seeks information or advice for patient care in an informal face-to-face discussion) of primary care physicians with integrated behavioral health specialists are described as a key element of the collaborative care model in order to help identify the best decisions for patient care needs. It also serves as a teaching and educational moment for human resources in the system. However, it is an underutilized function in real-world implementation because it is left to occur in an ad hoc manner with no design to facilitate, encourage, or monitor when or how it occurs.

Challenge 3: Clinical models are typically described and presented primarily using text-based toolkits [18] with minimal visualizations. Neuroscience has shown that images are processed in as little as 13 ms [19], while integration of processes that allow for word recognition takes 200 ms [20]. Specifically relevant to healthcare, Tien et al. state "Constructing and communicating a mental image common to a team of, say, clinicians and nurses could facilitate collaboration and could lead to more effective decision-making at all levels, from operational to tactical to strategic. Nevertheless, cognitive facilitation is especially necessary in operational settings which are under high stress" [21]. Visual representations have the ability to relieve much of the cognitive burden of reading, comprehending, translating, and processing verbal materials in a fast paced clinical environment. Not having visual models translates to a minimal ability to first, relay the clinical model sufficiently and thoroughly when attempting to get buy-in from a clinical team for implementation and second, implement the model in an easy and time and resource efficient manner.

Challenge 4: Clinical models are typically described by the most expected paths, rather than a comprehensive list of possible paths. Justification to only model expected or typical paths are two-fold. *First*, it is assumed that being comprehensive distracts from the core model with unnecessary information. Not being comprehensive translates to not noticing or classifying any deviations from the expected path. This allows clinical decision making biases to persist unseen, a significant problem in healthcare [22,23]. Therefore, modeling comprehensively is key to identifying and reducing problematic variations in clinical practice due to clinician decision-making biases.

Second, decision paths are described from the providers' perspective rather than the patients' perspectives. While there have been significant efforts to shift the discussion of clinical decision-making from the clinician to a shared-decision between the patient and clinician [24,25], the focus of shared-decision making is made at specific times rather than for every healthcare system interaction with the patient. Taking into account patient choice at each level of the modeling allows for the explicit elucidation of patient drop-out and non-compliance. This allows for the quantification of not only services provided, but to which types of patients and with what outcomes.

Challenge 5: Clinical models are typically described with minimal to no specificity of implementation-level details. This is particularly evident where details are needed at the mid- to most-specific detail-level description of the model. While healthcare environments vary and it may be best to leave certain details to the implementer, it is critical to be able to specifically describe the aspect of the tested model, which yields the success outcomes claimed by the model. This helps to inform implementers of the critical and more optional components of the tested clinical model.

1.3. Paper Contribution—Systems Thinking Approach to Tackle Current Clinical Modeling Challenges

This paper presents and uses systems thinking and systems engineering principles and tools as an alternative strategy to thinking about and designing clinical system models and healthcare services to alleviate many of the current healthcare clinical modeling design challenges. This allows current clinical models to be described as system models with *multi-level detail* and *quantification*, currently limited in clinical models. Systems thinking as a process also produces transparency and invites collaboration and understanding across all involved stakeholders. In doing so, stakeholders gain appreciation for the complexity across the healthcare system and insights as to how their own behavior affects patients, other healthcare personnel, and the healthcare delivery system.

1.4. Paper Outline

The background, in Section 2, will first describe a systems thinking approach to modeling healthcare delivery. This includes a description of the domains applying systems thinking to the health field and a systems thinking approach to healthcare delivery. Section 3 includes an illustrative example of taking a clinical model, called the Collaborative Care Model (CoCM) and developing a system model. This includes a description of the Collaborative Care Model, the methodology for developing the system model, and a detailed description of the developed system model. Section 4 includes a discussion of advantages and limitations of systems thinking in modeling and designing healthcare delivery services and models. Finally, Section 5 ends with the paper's conclusions.

2. Systems Thinking Approach to Modeling Healthcare Delivery

The health field, similar to most of the sciences, is based on reductionist thinking [12], breaking things down into their components and examining each of the pieces separately. On the opposite end of reductionist thinking is systems thinking. Systems thinking is based on examining the full system, its pieces, and interconnections to understand the system. The idea of systems thinking has been used in many fields and actually does not have a very clear definition. This special issue states that "Systems thinking can be broadly considered the activity of thinking applied in a systems context, forming a basis for fundamental approaches to several systems disciplines, including systems engineering, systems science, and system dynamics".

2.1. Domains Applying Systems Thinking to the Health Field

Systems thinking and systems engineering methods and tools have been used as exemplars across the health field. This section, however, focuses on the fields that have emerged that draw significantly from systems thinking [26]. These include Systems Biology and Healthcare Systems Engineering.

Systems Biology can be broadly viewed as a convergence of molecular biology and systems theory where the focus shifts to understanding the system structure and dynamics rather than the static connections of the components [27–37]. One of the goals of systems biology is to understand a complex biological process in sufficient detail to allow for the building of a computational model. This model would then allow for the simulation of system behavior, thus elucidating system function [38]. This can be viewed as applying systems theory at the cellular and sub-cellular level, one of the smaller physical scales.

Healthcare Systems Engineering is a relatively new field that applies systems theory and systems engineering tools to healthcare delivery primarily in acute care (e.g., intensive care unit (ICU), emergency department (ED)). This field can be viewed as an application of industrial engineering and operations research to health [39]. It is primarily focused on informing administrative stakeholder decision-making based on computational optimization of time and cost [39]. It is primarily focused on quantitatively representing the system in order to use optimization techniques for applications ranging from scheduling [40–45], reducing errors [46], improving hospital outpatient flow [47,48], improving emergency room operations [49], and improving patient safety [50].

This section presented the two primary domains specifically focused on using systems thinking tools and methods. It is worth noting that many applications of system tools (e.g., system dynamics [51], social network analysis [52], and agent-based simulation [53]) have been used across the health field to glean insights. It is beyond the scope of this paper to describe all such applications.

2.2. Systems Thinking for Healthcare Delivery

Next, a formal description of healthcare delivery as a system is described based on systems thinking principles that specifically addresses both acute and chronic conditions [15]. It begins with describing a system in the most abstract terms, its characterization by its system function, system form, and the allocation of function to form, called the system concept. This section highlights the application of systems thinking to developing a system model representation of personalized healthcare delivery and managed individual health outcomes [15].

2.2.1. System Function

The healthcare delivery system is composed of processes representing system function (i.e., the function of a system). Four types of processes have been previously defined in the literature [15] based on merging two concepts: the clinical diagnostic framework of measure, decide, and treat [54] and engineering systems functional type classifications of transform and transport [55]. The clinical diagnostic framework first examines the patient's complaint or concern (measure), second, decides on the cause of the issue or how to proceed next (decide), and third applies a treatment regiment (treat or transform) [54]. The healthcare delivery system function is thus represented as the union of the following four processes: *Transformation Process*: A physical process that transforms the operand: specifically the internal health state of the individual (i.e., treatment of condition, disease or disorder); *Decision Process*: A cyber(non-physical)-physical process occurring between a healthcare system resource and the operand: the individual, which generates a decision on how to proceed next with the healthcare delivery system; *Measurement Process*: A cyber-physical process that converts a physical property of the operand into a cyber, (i.e., non-physical, informatic) property to ascertain health state of the individual; and *Transportation Process*: A physical process that moves individuals between healthcare resources (e.g., bring individual to emergency department, move individual from operating to recovery room).

2.2.2. System Form

The healthcare delivery system is composed of resources representing system form (i.e., the components of a system). Four types of resources have been previously defined in the literature [15], similarly to system function. The healthcare delivery system form is thus represented as the union of the following four resources: *Transformation Resource*: A resource capable of a transformative effect on its operand (e.g., the health state of an individual). They include the set union of *human* transformation resources (e.g., surgeon, cardiologist, psychologist) and technical transformation resources (e.g., operating theaters, drugs, chemotherapy infusion room, delivery room); *Decision Resource*: A resource capable of advising the operand, an individual, on how to proceed next with the healthcare delivery system. They include the set union of human decision resources (e.g., oncologist, general practitioner) and technical decision resources (e.g., decision support systems, electronic medical record decision tools); *Measurement Resource*: A resource capable of measuring the operand: here the health state of an individual. They include the set union of human measurement resources (e.g., MRI technician, sonographer, phlebotomist) and technical measurement resources (e.g., magnetic resonance imaging scanner, ultrasound machine, hematology analyzers); and *Transportation Resource*: A resource capable of transporting its operand: the individuals themselves. They include the set union of human transportation resources (e.g., runners, emergency medical technician, clinical care coordinator) and technical transportation resources (e.g., ambulance, gurney, wheelchair).

2.2.3. System Concept

The allocation of system function to form then allows for the composition of a matrix representing a bipartite graph between system processes and resources, which is referred to as the system concept. This allocated matrix is defined as the system knowledge base [56–62] and represents the elemental capabilities that exist within the system.

3. Designing Clinical Models Using Systems Thinking and Systems Methodology: An Illustrative Example

This section takes a current clinical model and develops it into a system model as an illustrative example of a clinical model represented using elements from systems thinking. The example is of a service model that embeds behavioral health (BH) care into primary care. The remainder of this section describes the clinical model, followed by the methodology for developing the system model, and finally presents a detailed description of the designed system model.

3.1. Clinical Model of Behavioral Health Integration into Primary Care

Behavioral health care is a broad umbrella term used to encompass care for patients around mental health, substance use conditions, health behavior change, life stresses and crises, as well as stress-related physical symptoms [63,64]. Growing recognition for behavioral health needs makes this example critical and timely. The National Academy of Medicine has highlighted the importance of health care's recognition of the interaction of physical, mental, and substance use issues when providing health care [65].

The importance of behavioral health has been echoed by many sources, including the World Health Organization (WHO) [66], the Agency for Healthcare Research and Quality (AHRQ) [67], and the Substance Abuse and Mental Health Services Administration (SAMHSA) [68]. The call to action has been strengthened by recent federal and state actions, including the Mental Health Parity and Addiction Equity Act of 2008 ensuring parity in coverage between behavioral and physical conditions and the Patient Protection and Affordable Care Act (ACA) of 2010 containing many provisions promoting integrated behavioral and physical care delivery.

There currently exist several clinical models that describe varying levels of integration of behavioral health into primary care. One of the typically referenced models is the Collaborative Care Model (CoCM) based on the IMPACT trial [69]. The Collaborative Care Model was developed by the University of Washington's Advancing Integrated Mental Health Solutions (AIMS) Center [70]. It is typically presented using the Collaborative Care team structure visual, published initially in 2015, Figure 1 [71], and updated in 2017 with a newer visual, Figure 2 [70]. CoCM includes several figures that describe certain aspects of the model, such as the stepped care aspect of the model (where a stepped intensity level of providers are enlisted if insufficient results are being achieved) [72], or the step-by-step guide to implementing the model (described as a one-page document of high level tasks) [73]. The closest representation of functions and activities is described by the task list in Figure 3.

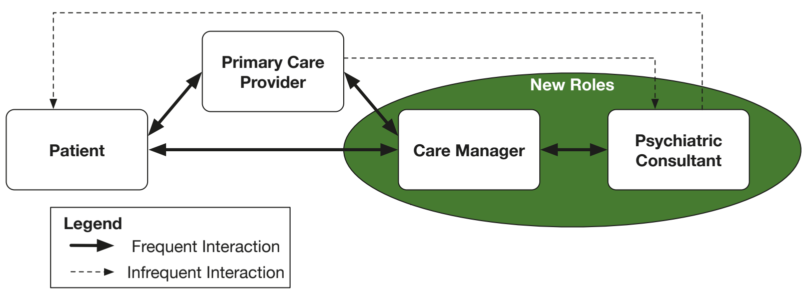

Figure 1. Collaborative Care team structure from 2015 (adapted from works created by the University of Washington Advancing Integrated Mental Health Solutions Center, 2015, [71]).

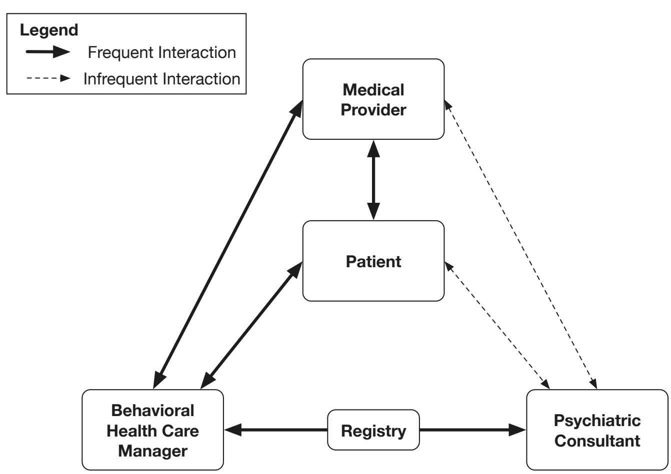

Figure 2. Collaborative Care team structure from 2017 (adapted from works created by the University of Washington Advancing Integrated Mental Health Solutions Center, 2017, [70]).

Core Components and Tasks

1	Patient Identification and Diagnosis
	Screen for behavioral health problems using valid instruments
	Diagnose behavioral health problems and related conditions
	Use valid measurement tools to assess and document baseline symptom severity
2	Engagement in Integrated Care Program
	Introduce collaborative care team and engage patient in integrated care program
	Initiate patient tracking in population-based registry
3	Evidence-Based Treatment
	Develop and regularly update a biopsychosocial treatment plan
	Provide patient and family education about symptoms, treatments, and self management skills
	Provide evidence-based counseling (e.g., Motivational Interviewing, Behavioral Activation)
	Provide evidence-based psychotherapy (e.g. Problem Solving Treatment, Cognitive Behavior Therapy)
	Prescribe and manage psychotropic medications as clinically indicated
	Change or adjust treatments if patients do not meet treatment targets
4	Systematic Follow-up, Treatment Adjustment, and Relapse Prevention
	Use population-based registry to systematically follow all patients
	Proactively reach out to patients who do not follow-up
	Monitor treatment response at each contact with valid outcome measures
	Monitor treatment side effects and complications
	Identify patients who are not improving to target them for psychiatric consultation and treatment adjustment
	Create and support relapse prevention plan when patients are substantially improved
5	Communication and Care Coordination
	Coordinate and facilitate effective communication among providers
	Engage and support family and significant others as clinically appropriate
	Facilitate and track referrals to specialty care, social services, and community-based resources
6	Systematic Psychiatric Case Review and Consultation
	Conduct regular (e.g., weekly) psychiatric caseload review on patients who are not improving
	Provide specific recommendations for additional diagnostic work-up, treatment changes, or referrals
	Provide psychiatric assessments for challenging patients in-person or via telemedicine
7	Program Oversight and Quality Improvement
	Provide administrative support and supervision for program
	Provide clinical support and supervision for program
	Routinely examine provider- and program-level outcomes and use information for quality improvement

Figure 3. Collaborative Care tasks (adapted from works created by the University of Washington Advancing Integrated Mental Health Solutions Center 2012, [74]).

While the CoCM is considered a clinically successful model, "the degree of integration of behavioral care into the primary care setting can vary from selective screening, diagnosis, brief treatment, and referral to a truly integrated care approach in which all aspects of primary care recognize both the physical and behavioral perspectives" [75]. This statement describes the dissociation between the description of the model and many varying levels of implementation across different healthcare delivery systems.

3.2. Methodology for Developing the System Model

A team at a local hospital was assembled and tasked with integrating behavioral health into primary care for an initial implementation at a test site, to be further rolled out in the future as a system-wide model to several other sites. The team included a systems engineering researcher and a range of personnel from the Departments of Psychiatry and Internal Medicine. The team proceeded to develop the hospital's integrated behavioral health service, with a heavy focus on the clinical aspect of the model followed by the operational aspect of the service model. This one-year implementation environment and process provided the knowledge needed for the development of the system model from an engineering perspective. Developing the system model of the CoCM was achieved in two steps: (1) by first describing system function, form, and context and (2) graphically representing the system.

First, the healthcare service model was described from a system function and form perspective by identifying the processes and resources, using the methodology presented in Section 2 and described in more detail in prior work [15]. Next, the system context was constructed, describing the resources performing each function at several clinically appropriate levels. This included a high-level description of the model as is typically presented in healthcare and in other fields. Next, more specific levels describing the details of the operations were constructed. This was prepared so as to highlight specific pros of integration. The determination of resources, processes, and allocation of function to form at varying levels was accomplished in two ways and from two sources. First, the material and literature on the Collaborative Care Model was used to begin to develop the model. Next, the year-long experience shadowing, interviewing and meetinging at the implementing hospital provided the much needed details.

Second, the system model was represented using a systems engineering graphical language. As part of systems thinking and systems engineering, there exists a systems modeling language that maps English language structure into graphical elements [76]. It also involves a unique vocabulary for describing structure and function of a system and can therefore be thought of as a language. The model was graphed using the model-based systems engineering tool, SysML. Finally, the model was presented and validated through individual and group feedback from the hospital team integrating behavioral health into primary care.

3.3. Description of the System Model

This section describes the system model describing the integration of behavioral health into primary care based on the collaborative care model. The multi-level system model is described by three levels. The description of the model follows in the remainder of this section, organized by system function, form, and concept.

3.3.1. System Function

System function refers to the services provided. As described in Section 2.2.1, the function of providing behavioral health within primary care in accordance with the CoCM was decomposed into several processes organized into three functional levels. Following the clinical diagnostic framework, a **high-level functional model** of Integrated Behavioral Health (BH) is presented in Figure 4.

It is composed of four functions: a function describing the engagement of the patient with the healthcare delivery system and the three functions from the clinical diagnostic framework. Specifically, *Function 1, Engage* patient describes the collective functions by which patients engage, interact, and enter the healthcare delivery system. This includes phone calls to make appointments, administrative check-in (e.g., check in at the reception desk) and clinical check-in (e.g., room patient, take vitals) processes that generally occur before a patient sees the primary care provider. *Function 2, Identify/Measure* behavioral health needs and severity describes the classic first step process of identifying and measuring a patient need and if required severity. *Function 3, Decide* on the care plan follows the identification of a behavioral health need. Deciding on a care plan incorporates understanding the patient's needs taking into consideration their wishes and circumstances and determining how to fulfill them. This includes deciding how to proceed within the healthcare system. This may include deciding to engage an integrated behavioral health clinician to provide therapy or measurement followup. It may also include deciding that more significant behavioral health services are needed beyond what may be provided within the integrated behavioral health service. In that case, direct referral to external services may occur, or a more active referral may be initiated. *Function 4, Deliver* service/treatment describes the delivery of treatments or services based on the developed care plan.

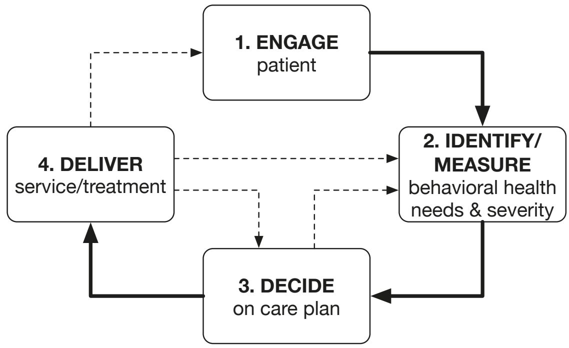

Figure 4. System Function: High-level functional model for Integrated Behavioral Health.

The **1st level functional model** of Integrated Behavioral Health, shown in Figure 4, is represented using SysML in Figure 5. These functional diagrams are called activity diagrams in SysML. This 1st level represents the primary care clinic-level system model without explicitly representing any specific integrated behavioral health functions. It shows patient contact or physical arrival (i.e., virtual or physical presence at the clinic) as inputs to this level. It also shows patients as outputs from this level when they are referred or supported into long-term external services. The figure also explicitly shows a significant problem in behavioral health, one of leakiness of patients coming from a patient's decision to not continue, follow through, or engage in next care steps, or their inability to remain engaged.

The **2nd level functional model** begins to show the details of the model classically recognized as collaborative care, as shown in Figure 6, and specifically in the Deliver Care dotted box. The 1st level identify/measure function described as "identify patients with BH needs" is functionally performed in the 2nd level by "determining and administering screening function". The CoCM health community typically names this step "systematic screening". The 2nd level functional model also specifically shows the decision function "determine needed BH services" as the gate to the options for BH services of the high-level deliver care function. It also makes it clear that there are four different types of internal services that integrated behavioral health services can provide in primary care. The details of each of these four services are described in the 3rd level functional model.

The **3rd level functional model** is the level where specific processes are defined and can be specifically allocated to resources. Interestingly, implementation teams allocate who will perform each process at the 2nd not 3rd level. This highlights that implementers have some form of a working visual model of the sequence of processes shown in the 2nd level in Figure 6, although this visual is not represented in any of the CoCM documentation figures. Implementers allocate at the 2nd level since most of the processes represented by the yellow rectangles can be assigned to a single provider; in this case, a primary care clinician resource or behavioral health clinician resource.

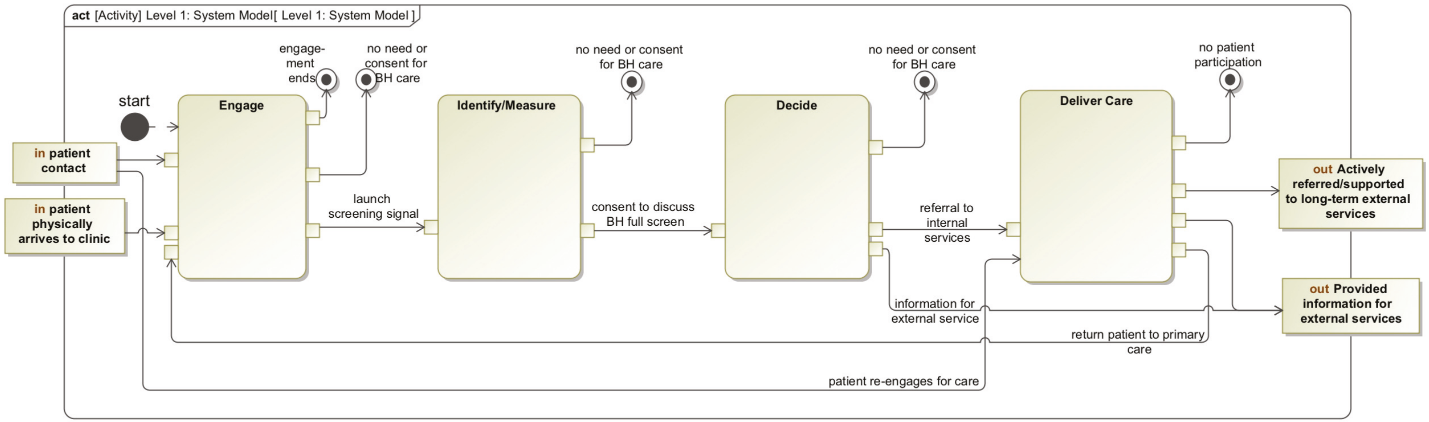

Figure 5. System Function: Level 1 Activity Diagram: Highest level functional model for Integrated Behavioral Health (BH).

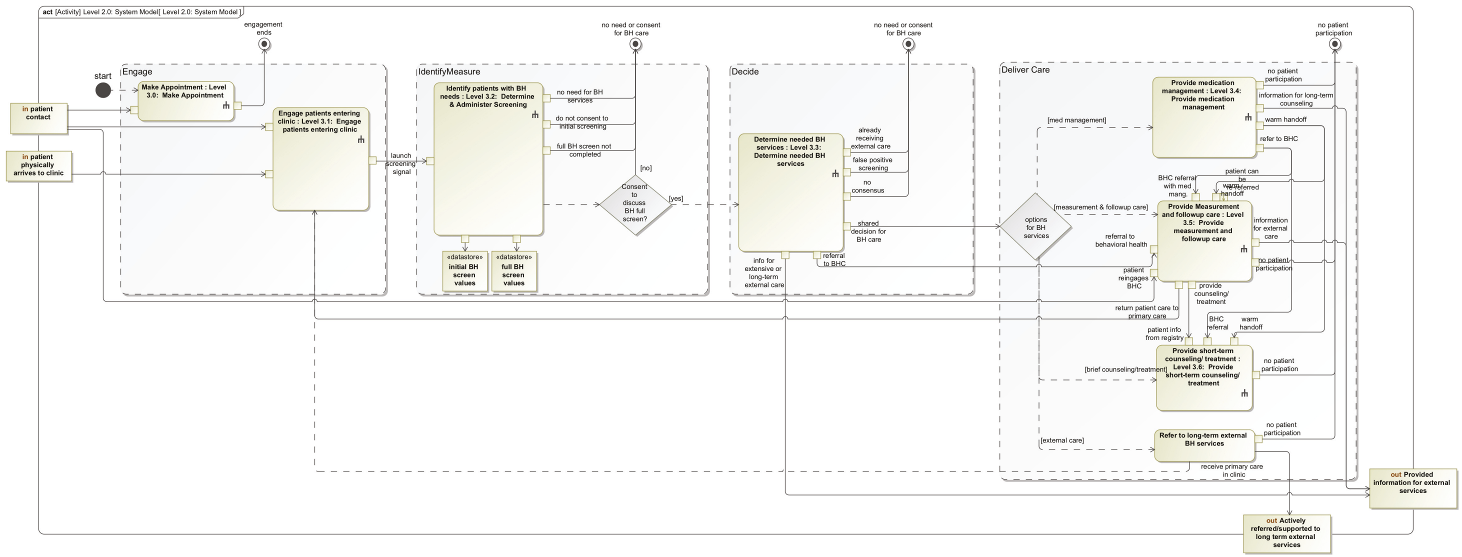

Figure 6. System Function: Level 2 Activity Diagram: 2nd level functional model for Integrated Behavioral Health (BH).

Many of the functions described as key aspects to the success of integrating behavioral health into primary care are processes that require the collaboration of two or more resources. For example, the decide function (Level 1) of "determine needed BH services" (Level 2) includes a key supporting task called "engage in curbside consult" (Level 3.3, shown in Figure 7), which occurs between a primary care clinician resource and a behavioral health clinician resource, shown with a red background. This is a key task that helps with quicker identification and faster directed care towards the appropriate services needed for the patient. This task also fulfills the function of educating and training primary care clinician resources to identify, determine, and provide behavioral health care more robustly.

A second example of this can be seen under the deliver care function (Level 1) of "provide medication management" (Level 2), which includes two key supporting tasks called "engage in curbside consult" and "warm handoff—introduce patient to behavioral health clinician" (Level 3.4, shown in Figure 8) and also shown with a red background.

Not specifically identifying the need for the additional clinical resource does not provide future implements with the details to recognize what functions require these multiple resource collaborations and how to design both of their workflows to ensure that they can both engage and perform these collaborative functions efficiently and consistently.

The development of system function using the activity diagrams allows for several noteworthy contributions. First, the clinical team providing services to patients include several types of clinicians: primary care clinicians, psychiatrists, and behavioral health clinicians. While, in theory, all clinicians may have a high-level understanding of the roles of their team members, the system model visually and cognitively clarifies the processes, flows, problems, concerns, and issues of how an individual's workflow can potentially impact other team members' workflow. This understanding was critical for implementation processes to minimize typical and current problems and dissatisfactions by colleagues and patients. Furthermore, it is important to note that the professional environment for healthcare human resources is very hierarchical, with medical doctor (MD) clinicians at the top and non-MD clinicians socially relegated to a lower clinician status. This modeling approach brought justification and voice to team members typically unheard or marginalized, whose information was invaluable in helping develop and improve patient care experience. This section described the functions performed in the CoCM detailing the processes and interconnections at three levels. We now turn to describing a system form that embodies and performs the processes described.

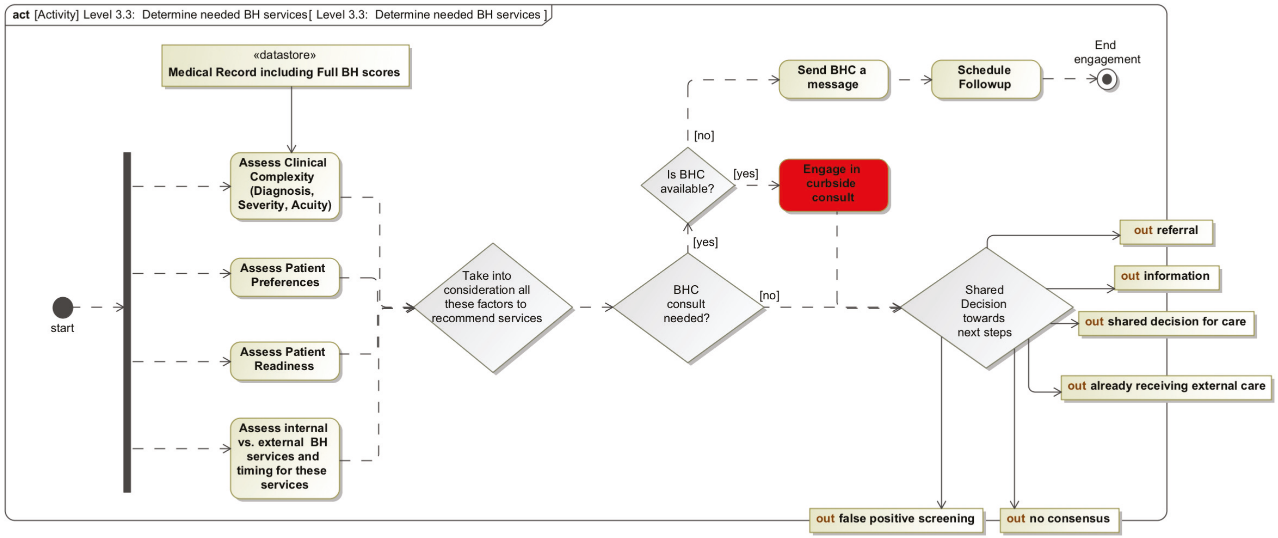

Figure 7. System Function: Level 3.3 Activity Diagram: Determine needed behavioral health (BH) services. The function highlighted in red is performed by two healthcare delivery system resources: a behavioral health clinician (BHC) and a primary care physician.

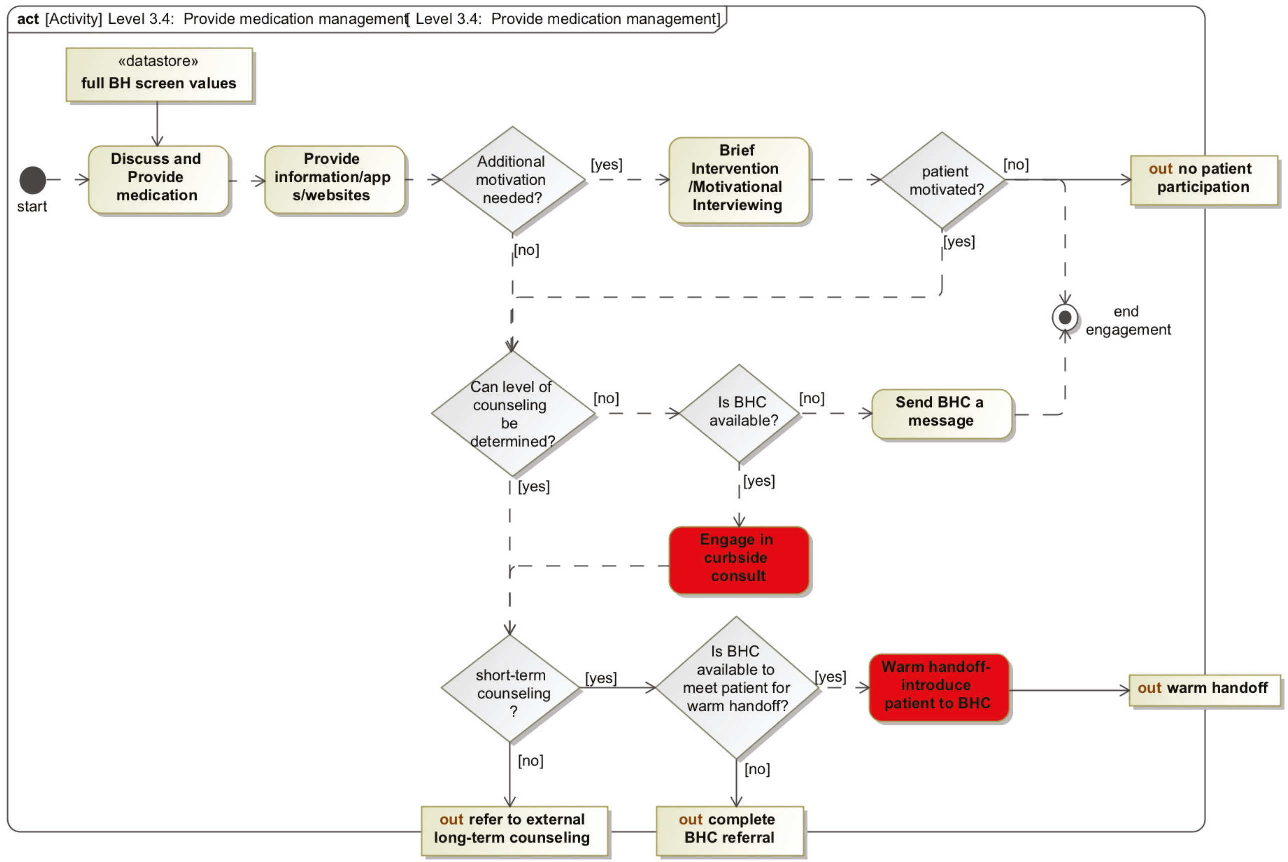

Figure 8. System Function: Level 3.4 Activity Diagram: Provide medication management. The functions highlighted in red are performed by two healthcare delivery system resources: a behavioral health clinician (BHC) and a primary care physician.

3.3.2. System Form

System form in healthcare includes the human and technical resources (i.e., the people (clinical and administrative) and the tools and rooms (the electronic medical record—EMR, examination materials, etc.). The human and technical resources in the CoCM are represented using a block definition diagram in SysML Figure 9. Resources are described at the level describing provider type (e.g., nurse, receptionist, primary care provider, behavioral health clinician). In the instance where the actual resource is identified, a specific human resource name would be included. For privacy, no specific names are included in the resource diagram. Resources are also grouped based on the system boundary they belong to (i.e., Integrated Behavioral Health Service, Department of Internal Medicine, Department of Psychiatry, or External System). The description of primary care and collaborative care personnel from different departments is highlighted in the background rather than described as part of the specification of System Form. This is because these classes of personnel are typically part of different departments, but this may not be the case in every implementation site. An allocation from the external system showing counselors allocated to collaborative care represents the instances when more personnel or specific types of personnel, such as counselors, are brought in to support collaborative care. The External System may include some, none, or possibly more services than have been shown. The classes of community behavioral health services included are ones typically needed when behavioral health needs are identified. The typical types of external resources are represented in the model, however, as one may speculate, the specific types and numbers of external services vary based on the implementation site.

3.3.3. System Concept

System concept refers to the allocation of function to form, or, in other words, what (function) is performed by who (form). This is visualized in the allocation matrix in Figure 10. The allocation makes clear what processes are performed by which resource or groups of resources. In many instances, both technical and human resources are allocated to performing a specific process. Such a mapping allows implementing organizations to decide, based on their own resource availabilities, how to perform the needed tasks and therefore create their own system concept. For example, the function of "referring to long-term external behavior health services", typically performed by a behavioral health clinician can instead be performed by a social worker who is not licensed to provide behavioral health treatment, thus freeing up behavioral health clinician time to perform other functions that require behavioral health expertise.

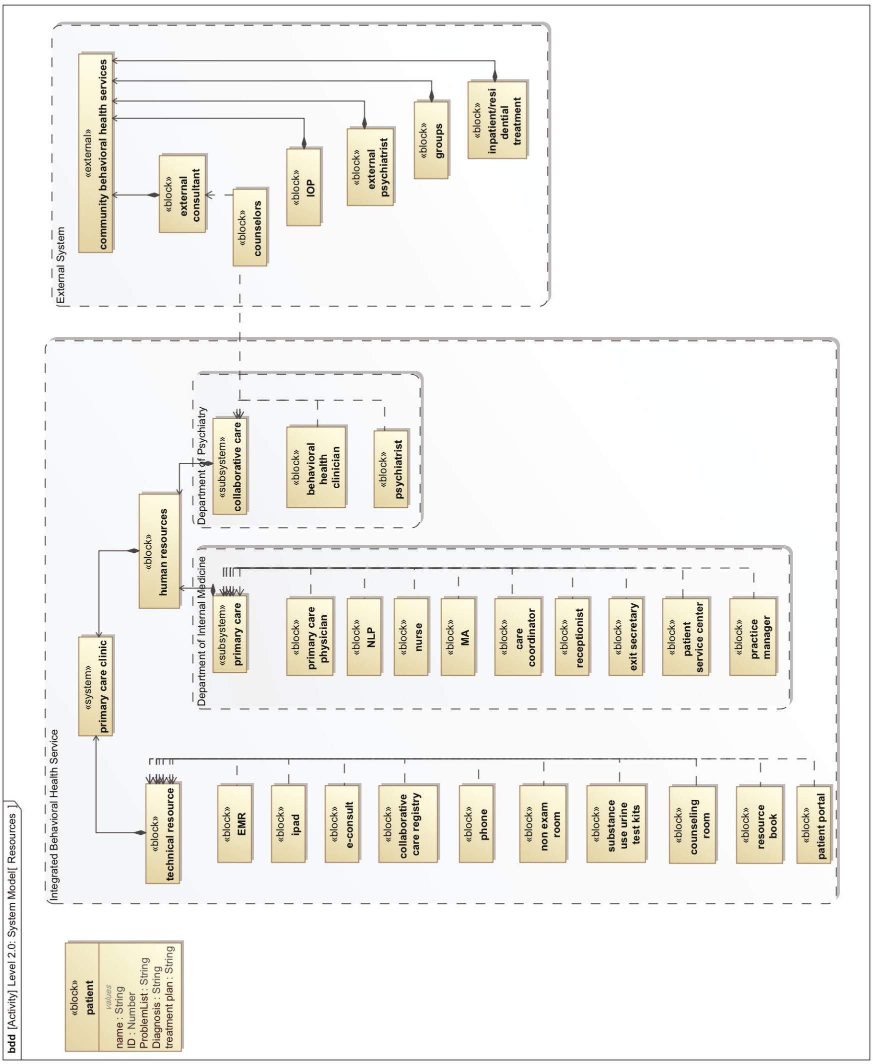

Figure 9. System Form: Resources for Integrated Behavioral Health.

	behavioral health clinician	collaborative care registry	counseling room	EMR	exit secretary	ipad	patient	patient portal	patient service center	primary care physician	psychiatrist	receptionist
Level 3.0: Make Appointment(patient contact, engagement ends)				12					24			
Add patient to provider schedule slot									X			
Allow patient to choose available provider appointment slot				X								
new patient?				X								
Provide orientation to behavioral health/holistic practice									X			
Provide orientation to general practice									X			
Receive contact and direct appropriately									X			
Level 3.1: Engage patients entering clinic(launch screening signal, patient conta				30				6				24
Ask standard check-in questions (i.e. do you have a cold...)				X								X
Check-in electronically								X				
Check patient in as arrived to clinic				X								X
Collect appropriate payment (if possible)				X								X
Require screening for this patient at this visit?				X								
Verify patient information				X								X
Level 3.2: Determine & Administer Screening(full BH screen not completed, Full				18		12						
Administer BH Full Screen				X		X						
Administer BH Initial Screen				X		X						
previous BH positive full screen?				X								
Level 3.3: Determine needed BH services(referral, information, false positive sc	6			12	6		6			42		
Assess Clinical Complexity (Diagnosis, Severity, Acuity)										X		
Assess internal vs. external BH services and timing for these services										X		
Assess Patient Preferences										X		
Assess Patient Readiness										X		
Engage in curbside consult	X									X		
Schedule Followup				X	X							
Send BHC a message				X						X		
Shared Decision towards next steps							X			X		
Level 3.4: Provide medication management(warm handoff, refer to external lon	12			6						36		
Brief Intervention /Motivational Interviewing										X		
Discuss and Provide medication										X		
Engage in curbside consult	X									X		
Provide information/apps/websites										X		
Send BHC a message				X						X		
Warm handoff- introduce patient to BHC	X									X		
Level 3.5: Provide measurement and followup care(internal referral, patient co	10	18		36							6	
Amend eDH note	X			X								
Assess patient readiness to begin BH care (in person/phone)	X											
Assess symptoms by patient reported information & Administer Phq9 +/- GA	X											
Call or meet with patient	X											
Contact patient by phone or MyDH	X											
Create relapse prevention plan	X											
Determine BH care needs (output decision into registry)	X	X		X								
Determine date of next contact	X	X										
Discuss case in Psychiatrist & BHC weekly meeting	X	X		X							X	
Note to PCP lack of interest or follow-through	X			X								
Provide patient w/ resource information	X											
Receive patient information	X			X								
Review goals of care plan & providers on care team	X											
Review meds for compliance, side effects, +/- adjustments	X											
Review safety plan	X											
Schedule 3 month follow-up encounter	X											
Schedule a 2nd call	X											
Update PCP on patient status (for possible med adjustments)	X			X								
Level 3.6: Provide short-term counseling/ treatment(BHC referral, warm hando	18		12	6								
Provide CBT	X		X									
Provide SBT	X		X									
Receive patient informatoin	X			X								

Figure 10. System Concept: The allocation of the 3rd level system functions to system form for Integrated Behavioral Health.

4. Discussion

This paper presents current challenges of designing clinical models and healthcare delivery services and presents a systems thinking approach to modeling healthcare delivery as an alternative framework to address the limitations presented in Section 1.2. An illustrative example of a clinical model, which embeds behavioral health services into primary care, was used to develop the system model. The remainder of this section highlights the advantages of system models over clinical models and the limitations of using such systems thinking models in healthcare delivery.

4.1. Potential Advantages of Systems Thinking Based Modeling

Systems thinking in healthcare delivery allows for five key advantages in system models that address the five challenges of designing clinical models, presented in Table 1. The five key advantages are presented in Table 2.

Table 2. Advantages of system models.

Advantage 1:	Designed based on **specified needs** rather than a specific diagnosis,
Advantage 2:	Described at **multiple levels and scales**,
Advantage 3:	Described **visually**,
Advantage 4:	Described with comprehensive paths; consequently, **quantitatively** describing the system, and
Advantage 5:	Described in multi-level detail, providing **a detailed multi-level implementation description**.

Advantage 1: System models are designed based on specified needs, rather than a specific diagnosis. The needs, also described as requirements in systems engineering, can come from patients with single or multiple diagnoses. Furthermore, since the system is designed to address specific needs, it becomes clearer to provide services that may help patients with multiple or complex diagnoses that have many different types of needs. The needs simply translate into a list of requirements that the system must be able to address.

Advantage 1 suggests that system models provide the ability over classic clinical models to describe and incorporate multiple patient needs, which need not be completely focused on a specific diagnosis. This is important and relevant since almost half of all people over the age of 45 have multiple chronic conditions [7].

Advantage 2: System models are inherently described at multiple levels and scales. Scope and scale are foundational concepts in systems thinking [77–79]. Diagraming a system at multiple levels is a core feature of system modeling [80,81]. Friedenthal et al. states, "An understandable model should include multiple levels of abstraction that represent different levels of detail but relate to one another" [80].

Advantage 2 suggests that system models provide the ability over classic clinical models to explain more clearly at the appropriate abstraction level the model details. This is critical for the multi-stakeholders that require different information from the model. For example, a high-level administrator would be interested in understanding the model of care implemented in their practice at the most abstract level, whereas a receptionist would need to clearly understand her tasks in detail. A classic clinical model does not provide the required information to all stakeholders.

Advantage 3: System models are described visually. Model-based systems engineering is by definition based on creating a *visual* model of the system. The focus on developing a model of the system is a shift from the traditional document based approach to systems engineering, where the emphasis is on producing and controlling documentation about the system [82]. The transition from the classic *text* document-based to *visual* model-based systems engineering occurred in the 1990s [83], while model-based approaches have been standard practice in electrical and mechanical design since the 1980s [80].

Advantage 3 suggests that a system model can be visually represented, whereas a typical clinical model is only described in narrative form. There are significant advantages to a visual representation. This includes the ability to see interconnections and interactions that may affect each other prior to implementation. For example, nurses suggesting a change to the method and type of data collected may not clearly pose an issue, but when checked in the system model would highlight how a specific data type is feeding into the data presented in a physicians dashboard.

Advantage 4: System models describe paths comprehensively. When modeling a system and specifically an activity, systems engineering methodology prescribes that all classes of inputs and outputs be described [78,79,82]. This ensures a comprehensive model and therefore allows the system to be quantitatively described. Situations which many clinical stakeholders may describe as having endless paths, are typically described in systems thinking by abstracting to generate a class of outputs representing a set of paths.

Advantage 4 allows system models to take into considerations paths that are typically ignored by clinicians because they believe they do not occur very often or they do not represent the focus of the model. It is critical to represent at least an abstraction of all outputs, since, when trying to understand problems in behavior, it is critical to ensure that all elements are included. This is an issue since recall abilities and perception of rates of occurrences of certain events may not be accurately recalled. For example, the role of the supporting psychiatrist in the CoCM is to have up to three clinical visits with a specific patient. Patient level data analysis, however, indicated many instances where a patient would see the psychiatrist for 10+ visits, indicating use of psychiatrists outside of the expected model.

Advantage 5: System models describe details at multiple levels, including implementation details [82]. Describing a model at multiple levels and scales to the very specific levels and scales leads to a comprehensive description that can be used for implementation. This is a natural conclusion given that engineering incorporates implementation as part of the engineering process [78,79].

Advantage 5 is critical in medicine. Engineering is naturally a field which develops and translates a solution as part of the same process. The medical research model, however, tends to follow a five-stage scheme of: T1 involves basic research, T2 involves pre-clinical research, T3 involves clinical research, T4 involves clinical implementation, and T5 involves implementation in the public health sphere [84]. Development separation creates significant delays in implementation and development, and does not take into consideration implementation science. This is an active concern of medical funding agencies [85].

4.2. Limitations of a Systems Thinking Approach in Healthcare Delivery

While the previous section presented several advantages of using systems thinking based modeling, it is also important to note possible limitations of a systems thinking approach in healthcare delivery. Three limitations have been identified and discussed below.

First, healthcare delivery systems have organized and structured their departments based on a reductionist view of the body into physical components of organ systems (e.g., cardiology, neurology, dermatology)—in other words, based on system form. This is the same mental construct used to develop clinical models. While this is exactly why there is a need for systems thinking, it is also a limitation in that the personnel in this field are not trained to think from a systems perspective. This may make systems thinking harder for healthcare personnel to grasp and understand. Systems thinking is not currently part of mainstream medical school curriculum. However, the importance of systems thinking in medicine and public health is evident in literature [86,87]. Furthermore, the Council on Education for Public Health (CEPH) (www.ceph.org) which provides accreditation to Masters of Public Health (MPH) programs and schools has now included "Apply systems thinking tools to a public health issue" as one of the foundational competencies expected of students when they complete a public health accredited degree. While systems thinking education and consequently knowledge in the healthcare field is limited, it is slowly being addressed and integrated into medical and public health education.

Second, introducing systems thinking to the healthcare field, especially to model current care, requires bringing in systems engineering personnel into the healthcare field. Although the importance of systems engineering in medicine has been presented in several high impact reports such as the President's Council of Advisors on Science and Technology [88] and the National Academy of Sciences [89], there still exists a limited number of systems engineers entering medicine relative to other fields. This is primarily because, at this early stage, there are limited systems engineering positions in medicine and healthcare delivery. The defense sector currently attracts a significant portion of systems engineering graduates.

Third, the current fee-for-service payment models in healthcare have forced clinical practices to increase throughput of patients, leaving the system with very little space to innovate, or add any new functionalities such as systems thinking and systems modeling. The fee-for-service system creates incentives for operations research focused on increasing throughput—moving patients faster through a poorly designed system. Systems thinking and system modeling take time from the already very fast pace and full schedule load of clinicians and personnel in healthcare. While there is much evidence to suggest that systems thinking could help alleviate some of the time-related issues by ensuring that processes are performed in an efficient manner (1) relative to how they are needed by the patient, (2) relative to the operations of the healthcare delivery system, and (3) relative to the use and need of other fellow clinicians across the healthcare delivery system in space (i.e., different department) and time (i.e., one month later), current fee-for-service payment models pose a limitation.

5. Conclusions and Future Directions

In conclusion, this paper presents and uses systems thinking and systems engineering principles and tools as an alternative strategy to thinking about and designing clinical system models and healthcare services to alleviate many of the current healthcare clinical modeling design challenges. An illustrative example taking a clinical model and describing it as a system model was presented based on the literature available and implementing an integrated behavioral health model of care into primary care at a local hospital. The developed system model alleviates many of the described clinical modeling limitations, by describing the healthcare delivery system from a systems perspective, in which system form, system function, and their allocation were described at multiple levels of detail. This allowed the model to be described at varying levels, including implementation-level details, from a patient-perspective. Such a description also facilitates the ability to evaluate and quantify the system at any of the levels. The process of developing the model was also just as useful as the model. It helped the team "see" things they didn't otherwise see, especially related to the work of co-workers and how an individual's work process can drastically affect a downstream co-worker work flow. This process in the described case example allowed the team to make process changes that improved both organizational and patient outcomes.

The culture and current work environment in healthcare delivery systems is a fast-paced environment, which does not typically reward organizations to slow down and self-assess and develop such clinical models. The typical fee-for-service payment models pose a limitation to the translation of this work since they incentivize high patient throughput over patient satisfaction and health outcomes. Luckily, in many organizations, the patient voice, patient needs and outcomes are so highly regarded and assessed that organizations are trying to accommodate and develop these new healthcare services and models regardless of current payment models. These frameworks can be used as a roadmap for organizations to develop services and models themselves, or to translate these services and models to their organizations using a more clearly described and enumerated model described at many levels of detail. Developing these models not only helps support new healthcare delivery services, but they also address many patient needs for integrated services and an integrated system experience. This work highlights the need to increase systems trained thinkers in healthcare and systems education in clinical and public health training and degree programs.

Future work will utilize the described modeling methodology and framework to enumerate both the healthcare delivery system and individual patient trajectories. This includes the use of this model in its enumerated form to address the generally high no-show rates seen for this service. This is not atypical for behavioral health and psychiatry visits, but did suggest room for improvement. Furthermore, designing quantifiable models (i.e., allowing for the evaluation of the system model) is often requested by high-level administration assessing their clinical services.

Funding: This research received no external funding.

Acknowledgments: The authors would like to thank the behavioral health design and implementation team members for their discussion and feedback. We would also like to thank Amber E. Barnato for her input and comments on this manuscript.

Conflicts of Interest: The author declares no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

MD	Medicine Doctor (Doctor of Medicine)
BH	Behavioral Health

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Article

A Bibliographic and Visual Exploration of the Historic Impact of Soft Systems Methodology on Academic Research and Theory

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Received: 12 December 2018; Accepted: 7 February 2019; Published: 13 February 2019

Abstract: Soft systems methodology (SSM), an analytic method commonly employed in engineering and business research, produces models focused on human activities and relevant structures used to explain complex, engineered systems. The original version of SSM involves seven stages; five address real-world aspects and observable data, while two stages leverage a systems thinking viewpoint. This approach allows the development of a simplified depiction of complex systems representative of the multi-perspective lenses used to comprehend the systemic complexity of a problem and provide a clearer picture to analysts and decision makers. This bibliometric meta-analysis of 286 relevant publications in engineering, business, and other social sciences fields explores the historic impacts of SSM on academic research and systems thinking in relevant publications that described or employed SSM for research from 1980–2018. This study produced descriptive narrative outcomes and data visualizations including information about top SSM authors, author citation impacts, common dissemination outlets for SSM work, and other relevant metrics commonly used to measure academic impact. The goal of this piece is to depict who, what, why, when, and where SSM had the greatest impact on research, systems thinking, and methodology after nearly 40 years of use, as we look towards its future as a methodological approach used to comprehend complex problem situations.

Keywords: soft systems methodology (SSM); systems thinking; bibliometrics; academic impact of SSM; data visualization

1. Introduction

Checkland [1] explained soft systems methodology (SSM) as an approach to understanding complex problem situations one wishes to learn more about and are poorly understood. SSM is a methodology that has shown increasing use over time to address multifaceted business, learning, and engineering problems involving complicated factors and structures about which stakeholders may not agree. The difficulty of translating outcomes from analysis of "messy" or ill-structured problems into usable solutions resulted in some mild criticism of the speed and viability of the SSM process for moving the analytic outcomes into strategic or product improvement recommendations [2]. There is also limited research into the effectiveness of soft systems approaches over time for generating solution, in part because some analysts find the method's requirement of stringent research that requires interactions with stakeholders and complex data sets to be onerous. However, this may be a misguided view because the goal of the approach is often to learn more about a situation, not generate clearly testable solutions. In past attempts, some researchers applied only a portion of the SSM stems in their research, which may limit the method's effectiveness [3]. Other criticisms of the method include its slow speed, difficulty in using it with stakeholders during analysis or to implement suggested solutions; further, the complexity of the problems under study may limit its acceptance as a valuable research methodology by some academics or managers [4].

Checkland [5] noted that there are different ways of thinking about systems. Systems are a group of interacting elements or subsystems with a unified goal and defined by its boundary as well as the nature of the internal structure linking its elements (e.g., physical, logical, functional). "Hard systems thinking assumes that the world is a set of systems (i.e. is systemic) and that these can be systematically engineered to achieve objectives. In the soft tradition, the world as it naturally exists is assumed to be problematic; but, it is also assumed that the process of inquiry into the problematic situations that make up the world can be organized as a system" (p. S49–50). "Hard" systems may be considered as organized systems with features and goals upon which stakeholders agree. "Soft" systems often contain identified elements such as outcomes, processes, strategies, or other features about which there is imperfect stakeholder agreement. Further, the system elements may change dynamically in response to local needs as system participants learn new information about their own or external, related systems. However, it is difficult to retain agreement about the best way to organize complex systems permanently, requiring further refinement of agreed upon understanding among participants over time that is generated by continued discourses among participants.

Since early work on SSM by Mingers [6] in the late 1970s and early '80s along with Checkland's groundbreaking 1981 *Systems Thinking*, *Systems Practice* book [1] that formalized SSM as a research approach, it has become a means of understanding problems with no single answer for those conducting research in assorted social science fields. SSM is valuable in complex situations that involve multiple stakeholders and systems, especially where learning or making sense of the problem situation is the goal of the study. Other, modified versions of the methodology by Boardman [7] and other authors are used to support visualization of SSM data for the purpose of improving problem situations.

While many students and professors recognize the term "soft systems methodology", SSM's impact on in engineering, business, and other social sciences in the form of vetted, academic research outputs (e.g., peer reviewed articles, committee reviewed dissertations, etc.) is less understood. This leaves additional questions such about the measurable reach of SSM in these academic research areas. Who are the authors using the method to produce research? How extensively is the approach used for research? It is also important to understand where the outcomes of SSM research are published and, using commonly accepted impact scores for associated journals, as a general measure of the degree to which they are perceived to be impactful on academic research and thinking distributed in broadly available publications. Past research by van de Water, Schinkel, and Rozier [8] explored the publications where SSM was published up to 2007, along with an examination of the countries from which the authors and journals were located. Since that time, a significant number of publications have entered public databases, which requires examination of SSM on academic research and dissemination in the ensuing period. A constraint on this research is that many practical applications of SSM used in corporate and other organizational studies that employ SSM are not published. Therefore, their findings are not available for review and remain outside the scope of this study. Such studies are reserved for future research with other, more appropriate methods to that task.

This piece examined the impact of SSM on academic works through a bibliometric meta-analysis of pieces that discussed as an approach or employed SSM for research. We begin with an examination of how systems thinking and the related SSM approach are defined. An exploration of the use of SSM in the fields of business, engineering, and other social sciences then illuminates this research. A bibliometric analysis follows, focused on publications found to discuss or employ SSM to depict the impact of the approach over the last 35 or more years.

2. State of Knowledge and Practice

Current knowledge regarding SSM originated in theory and practice work around General Systems Theory dating back to at least the 1950s and 1960s in a period following World War II, as organizations sought to build complex physical and human systems. Since that time, some authors have built new analytic tools for producing more rapid depictions of SSM analyzed complex, including the conceptagon and Systemigrams [9] in the case of Boardman's [7] version of SSM. The goal of these improvements was to use the better visualizations of the complexity as a means of developing improved systems, whether they are often well-defined manufacturing and software products, or instead, more poorly structured organizational systems upon which agreement about their shape remains elusive or in flux, leading to new problem situations. The following sections review the relevant history of soft systems methodology and its development.

2.1. General Systems Theory

Systems thinking, as a term and set of processes, was first introduced and formalized in the 1950s. Originally labeled General Systems Theory (GST), it was developed as both conceptual framework and mathematically expressed theory, most notably by Ludwig Von Bertalanffy [10]. His original conception was that problems identified symptomatically in complex systems across different disciplines affected one another, but they had to be first described independently and then in terms of their interrelations to help researchers clearly understand how they affected one another. While this was only a starting point, GST allowed systems thinking to flourish across disciplines such as ecology [11], engineering [12,13], business and academia [2,12], and education [14]. Furthermore, significant original academic work was done over the last thirty years in multiple disciplines to meaningfully grow the value and use of systems thinking [3,9].

Systems thinking describes the act of examining and seeking to understand a system, an interlinked set of objects, people, actions, and subsystems in a cooperating mechanism or set of activities, as a complex, Gestalt whole [9]. Rather than requiring a person to attempt perception of a multifaceted system one small piece at a time without its inter-relationships; systems thinking seeks to present the entire picture as a means of identifying where different components meet, perform well, or require change. This approach still requires that an analyst shift their gaze from the whole system to the parts in a back-and-forth effort. It is this process that allows comprehension of how components fit together, interact, and depend on one another for the entire system to operate and achieve its overall function. Such holistic thinking permits the mind to discover patterns among each element that may not be immediately evident or emerge over time. This approach requires acknowledging situations surrounding the whole as they change and interact with other, interrelated wholes to create the system as stakeholders are likely to perceive it.

For some authors, systems thinking is synonymous with holistic judgement regarding a coherent phenomenon or conceptual framework. At its core, this systems thinking approach examines the interconnectedness of each part of the system, uncovering patterns regarding how different components work together to produce certain systemic outcomes, as well as what may hinder desired results. The Society for General Systems Research founders stated that systems theory "provide(d) a meta-level language and theory in which the problems of many different disciplines could be expressed and solved" [5]. Unfortunately, GST has not resulted in the substantive investment by scholars to produce a generalized, holistic view across disciplines. Instead, systems thinking expanded slowly over the last 65 or more years in fields such as education, biology, engineering, and increasingly focusing on components of supply, demand, and logistics in the fields of business and related engineering disciplines.

2.2. Soft Systems Methodology

To foster systems thinking about complex organizations and processes, Checkland [15] formalized separate definitions of hard and soft systems, calling his own research approach and related conceptual framework "Soft Systems Methodology" (SSM) [1]. This means of analyzing ill-structured, soft systems emerged from General Systems Theory and includes a seven-stage process for applying SSM. This approach requires the analyst to think both about the real world and the conceptual model of the system under study. The stages include: (1) Entering the unstructured problem situation; (2) expressing the problem situation; (3) formulating root definitions of relevant human activity systems; (4) building conceptual models from the root definitions; (5) comparing models with the real world; (6) defining desirable and feasible changes; and (7) taking action in the problem situation. SSM is a process of generating understanding that may be used by analysts to generate systemic improvement recommendations for a system under study and while it also provides stakeholders with a rich picture of an identified problem situation and related systems one wishes to learn more about. Depending on a researcher's view, the research outcome could be a clearer view of shared systems of knowledge organized by stakeholders, organizational structures, activities, processes, physical objects working in concert, or others, depending on how they are defined at the outset of a study [9].

Checkland [5] explained hard systems research as focused on analyzing well-defined systems with a goal of describing and understanding problem situations in which stakeholder agreement is lacking. Such systems interact with one another and, through examination of the points at which they touch, can be depicted to identify how they may be engineered to perform better. Thus, hard systems analysis is commonly used to seek solutions to a well-defined, agreed upon problem. By comparison, a soft systems research approach is often used to learn more about a poorly defined situation that one seeks to better understand, without necessarily generating testable solutions, though researchers sometimes do so. These soft systems are complex and, when viewed from outside, may be deemed mysterious. While not always the case, when humans are part of the system under study, involve complex cultural mores and multiple systems that interact in uncertain ways with unpredictable outcomes. This challenge stems from the often poorly defined boundaries and conceptual definitions of a system's component parts, subsystems, or complex relations between similarly sized systems. This problem is often because the system emerged and evolved organically in response to its environment and needs, so its form may appear chaotic at the outset of analysis. Since system changes may have been done quickly where acute problems exist, without consideration of the consequence of a decision, there may be many ways for the system to be improved to perform more effectively. Engineers and analysts are meant to inquire into whether the soft system can be organized into what Checkland [15] called a learning system. With a hard systems approach, the Observer sees the world as full of systems that they can engineer; that is, they see the world as systemic. By contrast, in soft systems approaches, the Observer sees the world as full of complexity and confusion. However, these features can be organized for exploration as a learning system, using a systems inquiry process. What is presented here is our understandings of Checkland's concepts resulting from a synthesis of readings. However, Holwell [16] offered historic a critique of many authors' views of SSM, leaving our own open to similar criticism. However, the focus of this research is not our depiction of SSM; rather, we sought to examine the academic impact of the methodology on disseminated literature in social sciences fields. The research methods employed to that end follow in the next section.

3. Materials and Methods

This study depicts the impact of soft systems methodology in the engineering, business, and other social research fields. To do so, a multi-strategy, bibliometric analysis [17] was performed on the term "soft systems methodology". This research approach, commonly used in information science studies, involved multiple data sources and analytic approaches. This methodology was deemed appropriate to gather the complex academic evidence available from different sources to help tell the story of the impact of SSM, as evidenced in published research and theory disseminated publicly.

To meet this goal, a positivist research method and conceptual framing was employed [18] as it was appropriate to our questions, despite SSM being a non-positivistic research methodology. Our numeric, though descriptive approach allowed longitudinal description of the academic use of the methodology, focused on qualities of the academic publications and public metrics. Taking this path allowed us to first observe and visualize the state of use over an extended period with the ability to interpret findings from that observation regarding the subjective impact of SSM generally on academic research outputs. Given SSM's as a qualitative methodology, an interpretivist or hermeneutic research approach may have been in better alignment; however, given the size of the data corpus and scope of each publication, analysis and explanation of hundreds of articles was impractical. Further, such an approach likely would have failed to meet our research goal, which was to provide a historical view of the impact of SSM as a method on academic research as evidenced in published pieces.

This methodology required capturing written pieces that we could directly evaluate for evidence that the pieces included direct discussion of SSM as a methodology, or employed it as a research approach with observable outcomes. Bibliometrics, as a data analytics research methodology, comes from the library and information sciences. It is used to capture quantitative outputs of information sources using descriptive and network statistics based on citations, authors, keywords, texts, and dissemination outlets. In this study, the method was used to identify trends, impacts by use, subjects, and fields that have adopted SSM. Some analyzed data and presented here is meant to provide context for readers less familiar with SSM as a research approach, including who the major authors and journals in the area are. By contrast, other outcomes are valuable for visualization to depict the impacts of published research over time. To hold the rigor of the publication outlets steady for this study, we examined only published pieces we could fully read through to determine whether SSM was discussed or employed for research. Therefore, we did not include conference proceedings, unless they were available for review beyond a short-form abstract. This approach left as our data sources peer-reviewed articles, books, book chapters, white papers, and dissertations/theses. To gather these sources, our data collection methods, which sought to be exhaustive, employed data mining and Boolean searches from multiple sources using the following approach.

3.1. Data Collection

Data was gathered from multiple sources to capture the largest possible dataset that met our requirements and build a comprehensive profile of the use of SSM since 1980. The following are the digital tools employed, though not necessarily in order, because finding primary source materials often required using more than one source.

- Harzing's Publish or Perish—This was the initial search tool used to collate the starting dataset. This data mining tool from Google Scholar collects publications based on keywords and produces a listing all articles, books, book chapters, dissertations/theses, white papers, conference proceedings, and reference citations. In addition to authors, titles, and publication names, the tool also provides citation counts and links to the pieces.
- University library databases—JSTOR, ERIC, Web of Science, and others were used in order to gather PDFs of each article for review to determine if SSM was, in fact, present in the publication.
- Research Gate—Many PDFs of SSM pieces were available by their authors for download on this site. Some were freely available, while others were provided upon request.
- Google and Bing searches—Boolean searches were used to find online posted PDFs when they were unavailable elsewhere, as well as to determine whether some mislabeled publications were conference proceedings, books, or chapters, rather than peer-reviewed articles.
- Publisher web sites—Some articles were only available through publishers and purchased, or were sometimes available for no cost.
- Amazon and Google Books—These were used to purchase Kindle or original books as necessary for review.

- Organization web sites—For those pieces not correctly labeled as conference papers, we gathered abstracts as confirmation that the full paper was available. If not, the piece was not included in the analysis.
- Scimago Institution Rankings—This site includes journal and country scientific indicators drawn from the Scopus database using Google PageRank algorithm to create rankings (called SJR ranks) for each dissemination outlet. When available, the site also includes h-index rankings. Both indices were included in the data corpus to gauge the impact of the journals in which SSM pieces were published. These do not include books, chapters, or most conference proceedings.

The Publish or Perish tool produced 1000 results, limited in the tool to those that included the full keyword terms "soft systems methodology" or "SSM". These pieces were located from the university library databases and other Boolean searches to produce the original corpus of data for review. Each piece was evaluated to ensure that the authors employed a variety of SSM that matched with Checkland, Boardman, or another author that had both described and tested their version in a research setting at least once. However, due to natural variations among authors' approaches that fit their theoretical view or naturalistic setting requirements, we could not hold these constant to say they are all true to a fixed version of SSM. However, each piece claimed to employ or describe a version of SSM they believed met basic criteria aligned to Checkland or another published conception of the approach. All other source outputs were integrated into the database. Using these data sources to build the database, we employed the following approach to analyzing the data to answer our questions as follows.

3.2. Data Analysis

To organize, clean, and, analyze or display the collected data, we followed Onwuegbuzie and Teddlie's [19] suggested approach for multi-strategy data analysis, though modified to fit our process that was dictated by our questions and sources, as described below. This included the following steps, though not always in this order because the process was recursive as new data was discovered and refined:

(1). Data transformation and reduction—These two stages were combined in a departure from Onwuegbuzie & Teddlie's approach because the transformation process was part of the reduction stage. PDFs of publications or hard copies of other texts were reviewed to determine if SSM was discussed or used for research. In the transformation, the qualitative data captured from reviews of the publications was quantized with a binary score of 1 representing the presence of SSM in a piece or 0 if not. Those that did not include SSM were eliminated from the database. Further transformation took place in classification of the pieces from the Publish or Perish mining process when determining if they fit one of the following criteria: (a) peer-reviewed articles, (b) books, (c) book chapters, (d) white papers, (e) dissertations/theses. The publications also had to be available for review, so most conference proceedings were eliminated. Columns with incorrect or irrelevant data (e.g., repeated search dates, publishers, etc.) were also deleted.

(2). Data integration—Research Gate, publisher sites, Scimago ranks, and other data assimilated into the database.

(3). Data comparison and correlation—Data from the different sources was compared and correlated to confirm that each produced the same results and corrections were made, adhering to the source with highest credibility (e.g., primary source). These two stages were combined also differed from Onwuegbuzie and Teddlie's approach because they were concurrently performed. Data that could not be confirmed, such as pieces that were identified as including SSM, but without observable evidence, was eliminated.

(4). Data consolidation—All data was consolidated into the database and primary source texts were organized in a digital folder, organized by subject area.

(5). Data display—Organized database outcomes were analyzed using the USA version of Microsoft Excel and the accompanying Quick Analysis feature to produce visualizations in the form of tables, charts, and graphs. The outcomes of the data display step are the core of our findings, presented in the next section.

This process allowed us to answer the following questions:

(1). What has been SSM's impact on academic discourses in business, engineering, and other fields since its inception as evidenced by yearly publication trends and journal impact factors?
(2). Where has thinking about SSM been disseminated most often?
(3). What disciplines have been most impacted by SSM?
(4). Who have been the major contributors to the development of SSM?

The cleaned, reduced data produced 286 publications referencing or employing SSM as a research approach and illustrate the impact of SSM on published academic works as a means of depicting its reach.

4. Discussion

The findings from our analysis show differing impacts of SSM, depending on field of study. The distribution of articles related to SSM varied considerably since 1980, with certain periods most highly representing its impact. Some authors had more outsized impact on the use of SSM and systems thinking than others. The following sections explore these outcomes with accompanying data visualizations.

4.1. Impact on Academic Discourses Represented by Publication Trends and Impact Factors

The first major outcome is the publication trend tied to soft systems methodology from 1980 to 2018 as we approach 40 years of SSM discussion and use. Since this research approach was meant to take a global view of SSM's impact on academic output, we did not discriminate by region, instead choosing to view academic impact as an aggregate, worldwide outcome. Figure 1 presents the number of publications that included some reference to SSM (1980–2018).

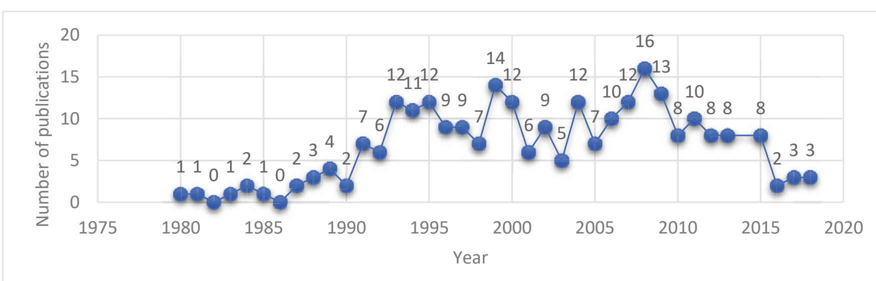

Figure 1. Number of publications by year (1980–2018).

In this figure, we see small growth in the 1980s, with a robust spike in use during the 1990s, following the publication of Checkland's [20] highly cited (569) piece in the *Human Systems Management* journal as well as Mingers and Taylor's [21] "The use of soft systems methodology in practice". Each piece simplified the process and provided examples that practitioners and theorists could apply. During that time more than 90 publications discussed or applied SSM in practice, showing high interest in the methods that continued through the 2000–2009 period. The period from 1990 to around 2010 included the largest number of SSM-related publications. With the decline in academic publications that employ SSM over the last three years, it is possible that the method may be perceived as inappropriate to answering today's research questions, or that they require more rigor than time allows. It may also be that some publications are not yet stored in databases accessible to the authors, so are unrepresented in this dataset. However, for those authors that have invested in the method and find it of value, this decline may be of concern if it is an indication that SSM's value is no longer clear to academic researchers. From an academic impact perspective, the outlets where SSM research and theory are published may also be of concern as noted in the next section.

4.2. SSM Most Common and Most Impactful Publication Outlets

While examining the impact of SSM as a function of the number of publication outlets is valuable to show how widely distributed the method is in academia, it is also important to understand where these pieces have been published to get a better sense of how accessible they are. Further, it is important to know the perceived impact of those journals that have been evaluated using objective measures such as SJR and h-index scores to provide a better sense of SSM's academic impact in the social sciences more broadly. The publication outlets that are most highly represented are included in Figure 2.

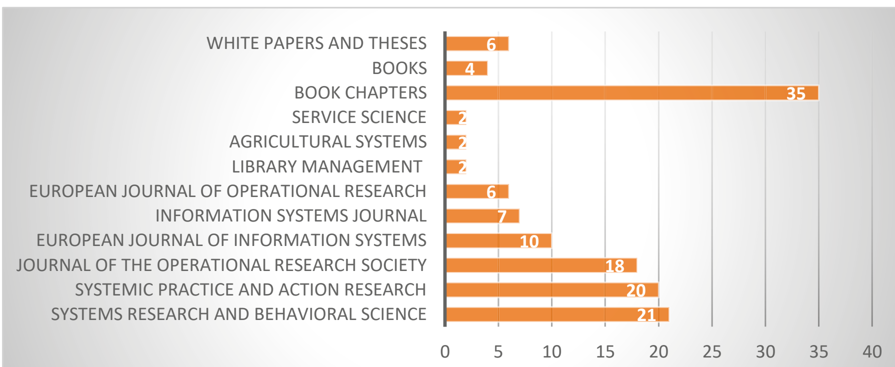

Figure 2. Highest frequency SSM publication outlets.

While the figure does not incorporate citation counts, the largest number of publications related to SSM are book chapters. This is problematic in academia, at least in the USA, because book chapters, like books, are less accessible to researchers that may be impacted by them. Finding and using book chapters as sources requires both knowledge that the edited book exists and a financial investment that many academics today may be unable or unwilling to make. This situation negatively impacts how broadly disseminated the research or theory outcomes are in academia and, in turn, limits the reach of SSM. Five of the top six journals that published SSM pieces are located in Europe, likely increasing knowledge of them and dissemination there. However, given the limitations of access to library databases in the USA due to increasing cost at higher education institutions, it is possible that researchers miss important SSM pieces, since the work is often behind a publisher paywall [22].

The top nine most represented journals each had published at least two SSM pieces, though only eight had citations because two of the pieces in Service Science were recently published. The following Figure 3 shows the citations for the top eight journals.

Systems Research and Behavioral Science was both a top destination for SSM pieces and had the strongest impact on the field based on citation counts. Most pieces in that journal were not research-based according to our analysis; rather, they discussed the development of SSM as an approach to research in a particular discipline. Many articles offered significant adaptations and additions to the methodology to make it easier to use or more applicable in different fields, but failed to report research outcomes from testing those changes. This is an issue noted by Holwell [16] with articles through the 1990s that continues to today. While Systemic Practice and Action Research included significant publications, the journal's impact was less evident on the field by citation count, though the number of research studies using SSM was greater than most other journals. However, the most significant publication outlets were not journals, as shown in Table 1.

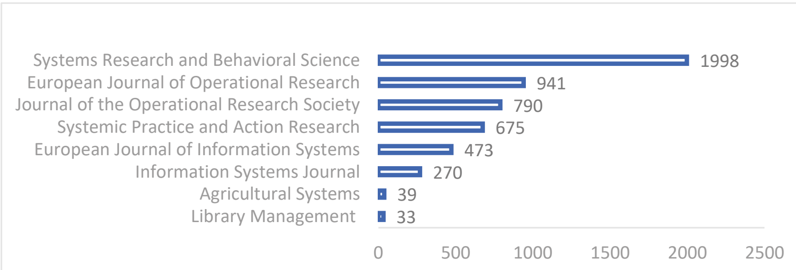

Figure 3. Top eight SSM journal outlets and citations of SSM-related articles.

Table 1. Citation counts for SSM-related publication outlets.

Dissemination Outlet	Citations
Books (66.91%)	18,052
Book chapters (13.44%)	3625
Systems Research and Behavioral Science (7.41%)	1998
European Journal of Operational Research (3.49%)	941
Journal of the Operational Research Society (2.93%)	790
Systemic Practice and Action Research (2.50%)	675
European Journal of Information Systems (1.75%)	473
Information Systems Journal (1.00%)	270

As mentioned earlier, limited knowledge about and access to books and book chapters reduces dissemination of ideas and research due to cost or marketing of materials, especially from one continent to another. This may negatively impact the reach of SSM in some regions, such as the USA where systems thinking topics tend to be associated with Senge & Sterman [23], Banathy and Jenlink [14], Reigeluth [24], or other authors that more commonly publish conceptual or "thought pieces" rather than research outcomes. With the heavy focus on positivist, numbers-driven research methods in the USA, it is possible that American academics' exposure to systems thinking from these sources has provided a limited picture of SSM and related methods. They may therefore view such approaches as less rigorous and, therefore, less valuable. This situation may account for the difference in where SSM pieces have been published as well, with European journals significantly more represented than in USA journals. This condition could indicate either an implicit or explicit bias among journal editors and researchers against soft research methods, and qualitative approaches more broadly, in different fields that must be overcome with better teaching and training [25].

For SSM as a topic of discourse and use as a research method, Figure 4 visualizes the high impact of four books and thirty-five book chapters had versus journals. 11,144 total book citations came from Checkland's and Scholes' 1990 book [26], which gave that publication the largest impact on other authors. Removing that text as an outlier, SSM-related books still had almost twice the citation impact of book chapters and nearly a treble impact over the top journal's pieces, limiting the impact of academic research pieces that employed SSM by comparison.

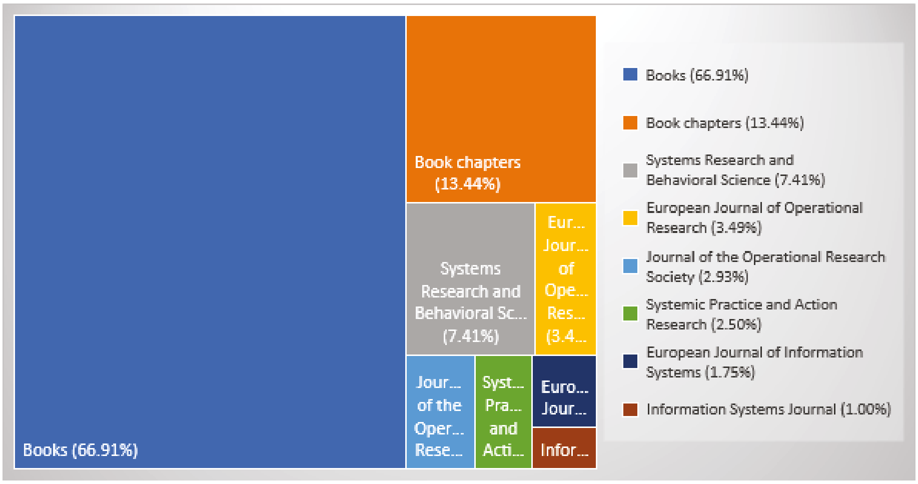

Figure 4. Citation impact of SSM dissemination outlets as a percentage of all citation.

Based on citation counts, books had the largest percentage impact by a significant margin, with book chapters following substantially lower. Chapters and books combined accounted for 80.35% of all measured SSM citation impact, the top journals accounting for only 19.08%. This means all other journals accounted for only 0.57% of all citation impact, which limits perception that the SSM work contained in them reached an interested audience, which may be partly responsible for the decline of published academic pieces that employ SSM in recent years. This differs by field, with some disciplines such as engineering and business showing historically stronger affinity with SSM methods than others. Findings regarding the disciplines impacted by publications containing information about or research using SSM are included in the next section.

4.3. Disciplines Most Impacted by SSM

To capture which disciplines are most impacted by SSM, each publication was reviewed and coded according to the Scimago journal subject area that most closely aligned with the content. While white papers, dissertations, books, and chapters do not have subject areas, those were coded in accordance with similarity to journal articles containing the same subject matter. Figure 5 presents the distribution of articles according to coding for Scimago subject area.

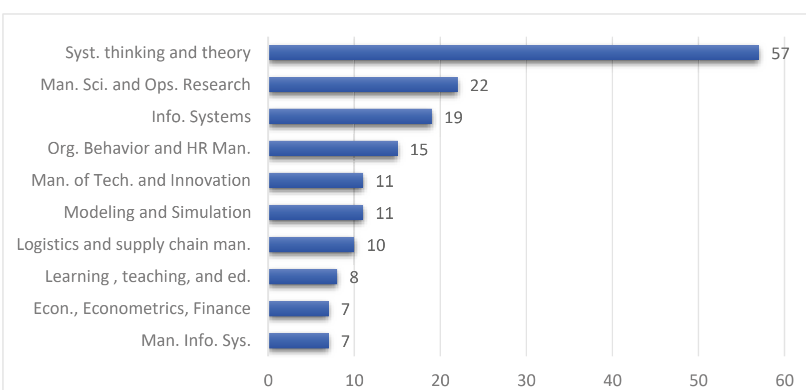

Figure 5. Top 10 SJR coded subjects of publications using SSM.

"Systems thinking and systems theory" constituted the largest subject, with "Management science and operations management" trailing considerably. This was, in part, because our content analysis revealed that most pieces coded as systems thinking and systems theory discussed the development of SSM from the perspective of a discipline, but often contained no research application. Most also only described proposed alterations of the methodology for a particular purpose [27] (e.g., software development by adding UML) or a description of SSM to a new audience [28,29] (e.g., marketing, medical settings, etc.) and failed to provide evidence of their effectiveness. The Scimago codes above were classified into broad subject categories based on the topics of the articles in the database and are presented in Figure 6.

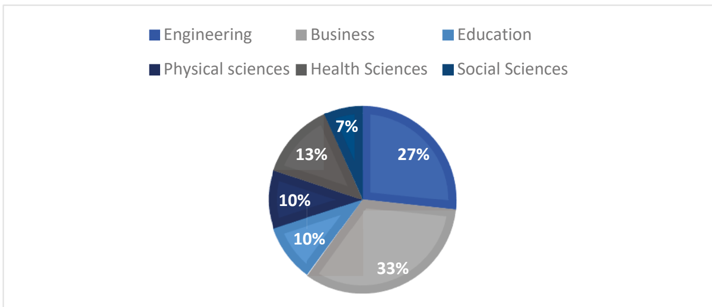

Figure 6. Disciplinary category representation of SSM-related articles.

Business was the largest discipline impacted by SSM research in publications from 1980–2018 with ten subjects represented. Engineering followed with eight highly coded Scimago subjects. Physical science category pieces tended to focus on large scale, messy problems like water allocation in countries with poor access to clean drinking water, making SSM an appropriate tool for research. Education and health sciences also had ill-defined problems that made SSM useful for studying complex systems and, while SSM was less impactful than with business or engineering, there was some influence. The authors that contributed to these pieces had differential impacts on SSM research and practice, as shown in the following section.

4.4. Major Contributors to SSM Theory and Research

As measured by the number of publications tied to SSM, twelve had the highest impact. These are presented in Figure 7, showing the percentage of the 286 SSM-related publications analyzed here that they are responsible for as an author since 1980. Each had three or more publications related to SSM.

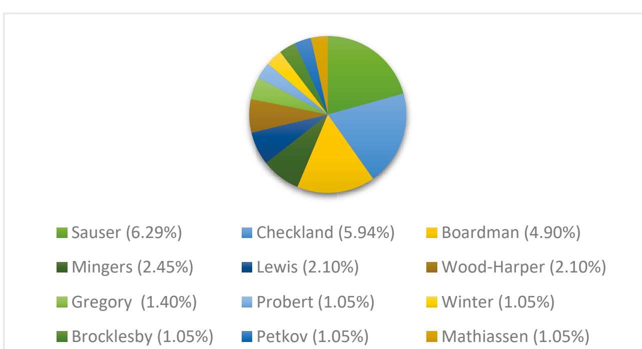

Figure 7. Top author representation among all SSM-related publications.

The top six authors combine to represent 23.78%, or nearly a quarter of all SSM-related publications since 1981. The remaining 75% of pieces written by other authors indicates a broad distribution of the ideas and application of SSM, with those above serving as what Lave and Wenger [30] called core participants in what may be considered Community of Practice centered on the development and use of soft systems methodology for academic research and theory development. While the distribution of the work is fairly broad, the following Figure 8 shows that the citation impact is substantially different.

Figure 8. Author impact on field by citation representation percentage.

Checkland's impact, as expected, is clearly massive, regardless of the field of influence. His work on SSM garnered 23,780 citations, with 11,114 alone for his 1981 book. Mingers contributed substantial work as well. Boardman, with his variant of SSM applied in engineering and business settings, and his work with Sauser, showed strong impacts among the remaining authors. However, with less than 23% of all citations coming from authors besides Checkland, the academic impact distribution of SSM as a research approach did not have the reach that its proponents may have hoped.

5. Conclusions

Since Checkland synthesized a coherent set of steps for soft systems methodology and Boardman developed his revised approach later, SSM has continued to evolve to address perceived challenges and new means of applying the principles in diverse disciplines. Boardman's significant contribution to the methodology and books on systems thinking significantly contributed to the expansion of use of SSM through his own version, commonly referred to as BSSM. His work to expand SSM into business and other disciplines is correlated with the major expansion of use of systemic diagrams as outcomes in research publications between 1993 and 2015. While the database search for SSM resulted in more than 32,000 citations, other soft research methods such as failure modes and effects analysis (228,524) and system dynamics (2,380,988) showed more impact by that measure. To grow the thinking about and use of SSM, we offer four propositions for improvement to soft systems methodology training and process.

- Improved university education

In Europe, where many of SSM's principles emerged and were formalized into method, graduate programs tend to teach it alongside the mathematically driven, positivist methods (e.g., linear algebra, regression analysis, etc.) common in USA business schools. However, outside of the books and articles that lay out the steps for SSM, limited formal training to use SSM currently exists in the USA outside of doctoral programs (e.g., Stevens Point, North Texas) that include faculty who have themselves received training. This is not an efficient means of transferring knowledge about how to employ the methodology in different contexts, relying as it does mainly on cognitive apprenticeship and where one chooses to attend university.

- Training using public media outside of academia

Improved training and knowledge sharing could also be accomplished through the development of publicly available online training videos with activities, massive open online courses or similar pedagogical approaches to further disseminate the methods and train a broader array of researchers. Doing so could increase awareness, ability to appropriately employ, and overall acceptance of SSM across disciplines. We believe standardized, broadly available training would add value to researchers and organizational leaders who want to understand how using SSM can benefit them. Such training could increase the overall number of users who employ SSM to understand their complex problem situations, also increasing the academic impact and acceptance of the approach.

- More SSM-based research published in diverse field journals

Exposure of academics to SSM research outcomes through publication of articles in journals outside of business and engineering fields is also important to increase the perception that it is a valuable tool for social science research. The more often researchers see academic outcomes that can be used to solve problems in a variety of fields, the more likely we believe they will be to use them. With significant examples of application, acceptance of both method and findings should increase.

- Increase the diversity of authors using SSM for academic research

For a research methodology and related concepts to take hold in academia, it must be taught broadly, used regularly, and accepted by editors and reviewers alike. However, it must also be used by a significant number of authors, rather than just a small group of about ten core participants noted earlier who are responsible for much of the academic discourse around SSM, or it will not grow. To improve this situation will require mentoring and discussion from these core participants at conferences, willingness to review for journals that publish SSM research, and supportive feedback in coursework and theses produced with the methods. However, this is an important part of the collegiality and social construction of knowledge central to the academic mission.

The findings reported in this article have several limitations; however, it is intended to start new conversations about how to grow SSM as a robust methodology in academia in the future. Because all research is imperfect due to incomplete information available at any time due to access (e.g., limited article database access, books out of print, etc.) and author cognition (e.g., lack of knowledge about sources, distance from alternate sources, etc.), we are likely to have missed some publication that one reader or another may find foundational. However, the sample of data in the corpus presented here indicates that SSM as a methodology had some significant impact on academic thinking in the USA and Europe from 1980–2018. While SSM provided strong value in the past and has the potential for greater impact across many disciplines in the future, increasing its use and acceptance in academic disciplines requires change. Modifications to practice and thinking about SSM should take place in university education, academic publishing, and in conference discourses to help foster improved researcher attitudes towards non-positivistic research methods in engineering, business, and other fields. Future SSM research outcomes can better explain the value of the methodology to those that would benefit from it in academia and be a means for growing field-specific knowledge regarding complex problem situations.

Author Contributions: Conceptualization: S.W. and B.S.; methodology: S.W.; validation: B.S. and D.N.; formal analysis: S.W.; investigation: S.W.; resources: S.W., B.S., and D.N.; data curation: S.W.; writing—original draft preparation: S.W.; writing—review and editing: S.W., B.S., and D.N.; visualization: S.W.; supervision, B.S.

Funding: This research received no external funding.

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

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Article

Could Education for Sustainable Development Benefit from a Systems Thinking Approach?

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Received: 12 November 2018; Accepted: 30 November 2018; Published: 4 December 2018

Abstract: Sustainable development is not a novel concept. However, we continue with our unsustainable way of living. It is as though we cannot see our own part in the unsustainable system. Values, ethics and morals are connected to education and therefor education is in a key position to change the way we think and act for a sustainable future. Both education for sustainable development (ESD) and systems thinking are concepts connected to changes toward a sustainable future. However, they have proven to be conceptually problematic and are characterized by their complexity, making implementation more difficult. The purpose of this study is to discover whether it could be possible to interlace ESD and systems education to a strong and solid entirety in order to overcome the obstacles preventing the implementation of sustainability in education. This is done through a literature review in the fields of systems thinking and ESD. The literature review identifies two joint approaches that could be worth exploring more in order to develop an excellent instrument in the educational work toward sustainability.

Keywords: education for sustainable development; sustainability; systems thinking; teacher education; systems education

1. Introduction and Background

The concept of sustainable development is not a novelty. One of the founders of the Worldwatch Institute, Lester Brown, coined the concept of sustainable development through his book "Building a Sustainable Society" [1], published in 1981. The concept of sustainable development became more widely known in 1987 through the so-called Brundtland Report.

The Bruntland Report [2] in the 1980s also stated that the unsustainable problems society was facing then (and in many ways is facing still) consisted of two different types of problems; on the one hand, poverty, hunger, illiteracy, homelessness and increasing income gaps, and on the other hand, deforestation, the development of desert landscapes, acid rain, global warming and pollution. Nowadays, these problems are linked to and defined as the social and ecological dimensions of sustainable development. Additionally, it is now quite obvious that these dimensions or problems are interlinked. For example, deforestation, the development of deserts and climate change cause something called climate refugees and increase poverty.

In the 21st century, sustainability has become something of a buzzword used in varying contexts [3]. It is now commonly accepted by the scientific community that the concept of sustainable development consists of four commonly defined dimensions, i.e., the economic, social, ecological, and social dimensions. To make the concept of sustainable development even more complex, the four dimensions also include several different aspects and dimensions which are complexly interrelated [4]. If we go back a few decades in history, to the late 1980s and early 1990s when sustainable development became more widely known, there were also some ideas presented on how to achieve a sustainable development. For example, in the United Nation's document "Agenda 21", published in 1992, education was mentioned as a key to achieving sustainable development and the concept "education for sustainable development" (ESD) became common in educational policy documents [4].

Many scientists are, however, critical of the use of the words "for" and "development" in the ESD concept, as they are considered to be normative. A new concept has subsequently become an alternative, named "sustainability education" [5,6]. The difficulty to find a common definition or agree on the name of the concept is one thing, but there is also no common consensus regarding the educational content of ESD, and this is probably one of the main reasons why it has been shown to be hard to implement in education [7]. A cold fact is that our planet Earth is still suffering, even after sustainable development became a common concept more than 30 years ago. It suffers from air pollution, biodiversity loss, deforestation and other problems [4] due to our continued unsustainable way of living [4]. Alarming global human issues today include overpopulation, access to water and sanitation and unequal distribution of food. One of the major environmental threats is climate change [4], which is interconnected with consumption [8] and thus a part of the unsustainable system. A Finnish research report [9] indicates that the Saami people, an arctic indigenous population, are particularly vulnerable to the effects of climate change. In a press release one of the researchers state that this is an ethical dilemma, as the Saami are one of the population groups living in interaction with nature and who probably bear less responsibility to climate change; however, the group will probably suffer most from the negative effects. To reunite man with the meaning of life, there is a need to change the prevailing mindset and change the relation to nature existing today toward living in interaction with nature as indigenous people often do [10].

But how can the mindset of humans be changed? Now, consumerism is the main focus of societies all over the world [11,12]. Consumerism is glorified as a requirement to achieving happiness, and according to the popular economic view, development and happiness are dependent on economic growth [13]. The common way to talk about prosperity is to identify prosperity with consumption and wealth. However, studies across countries show that increases in income per capita and levels of happiness are not correlating to any great extent [13,14]. In fact, research indicates that our consumerism is driving us in the opposite direction instead, toward illness and alienation from the social relations that increase our wellbeing [13]. It appears that values other than economics, for example living *with* (social relations) and *for* other people (doing things for others), are more important to human wellbeing [15]. This is an indication that our unsustainable lifestyles and consumption do not even give us the benefits we think they do and calls for a new way of thinking.

Changing the way we think is something that the United Nations Educational, Scientific and cultural organization (UNESCO) also touches upon in a more recent policy document, where education is highlighted as a key for transforming whole societies toward sustainable development in their Global Action Program on Education for Sustainable Development—Future Forward [16]:

> "Sustainable development can be achieved but technological solutions, political regulations or financial instruments are not enough. Long-term sustainable development can be achieved only if individuals and societies change the way they think and act. Education is key to achieving this transformation." [16]

Education is put in a key position to change people's way of thinking and acting, but there is no deeper discussion about how education is supposed to manage this change other than by building networks of key stakeholders. To develop new perspectives in education, a holistic understanding of the sustainability phenomenon is necessary [17]. To change the unsustainable way of living, Koger and Winter [18] propose an action-oriented environmental education for youths to develop confidence, self-esteem, critical thinking and problem-solving skills.

One of the current problems within the system today is how people react when facing environmental problems and environmental concerns. According to Koger and Winter [18], a common psychological reaction is denial, which is just one of a lot of defense mechanisms that humans have developed to continue to harm the nature and environment, even though we know it is wrong and that our actions will have bad consequences [18]. Apathy is also a defense mechanism that people have developed to continue with habits that affect the nature and environment in bad ways [18]. Almers [19] points at the importance of teachers' knowledge and behavior to prevent this form of paralysis when teaching about the effects and consequences of actions. She argues that to be able to develop an ability to make conscious choices, students need to have the opportunity to reflect on their own attitudes and actions in various issues.

Koger and Winters's [18] idea about an action-oriented environmental education relates to a great extent to Almers' [19] idea about learning and action competence, as she claims that the feeling of contribution through actions is important for students to develop confidence. She presents four aspects of teaching that are important to raise in every learning situation:

- What (descriptions of the effects and consequences of the problem)
- How (option on change and action strategies)
- Why (perspective on structural reasons)
- Where (goals and alternative solutions)

These four aspects are also to be found within systems thinking and systems education. Additionally, Salīte et al. [20] highlight the action research approach and systemic collective thinking as possible contributors to the development of continuing education and reorientation toward sustainable development.

Critical thinking, problem-solving skills and action are often mentioned in literature from both the research field in systems thinking [21–26] and the research field in sustainable development [4,19,27–29]. Development of a critical approach is often mentioned within both research fields. In addition, systems education is highlighted as a possible solution to societal problems in the book "Systems Education for a Sustainable Planet" [30]:

> "Systems education can help transition towards a sustainable planet, as it helps people appreciate that individual actions are not isolated events but contribute to an interconnected system that determines both the well-being of humans and the planet" [30] (p. 1)

Although systems education is crystallized as a possible pathway working toward sustainability, recent research [27] shows that Nordic student teachers possess low levels of systems thinking, indicating that the teacher education in the Nordic countries does not help student teachers to develop systems thinking. This is a remarkable issue as systems education requires systems thinking. Wolff et al. [4] also argue that the Finnish teacher education fails in sustainability. If the teacher education both ignores sustainability and does not manage to develop systems thinking within the student teachers, then systems education is far out in the shadows and could be very hard to establish within the present system of teacher education. As Fedosejeva et al. [17] state: the new generation growing up now has a completely different perception of the world than earlier generations. This calls for a complete re-organization of the study environment to develop the abilities and skills needed to live in and manage a culture that is different and unknown [17]. A re-organization of teacher education is crucial to re-organizing the study environment.

Perhaps systems thinking and systems education could be the missing tools needed to develop the holistic thinking required in the work toward a sustainable future. If that is the case, the big question is if and how it is possible to interlace ESD and systems education to a strong and solid entirety to overcome the obstacles preventing the implementation of sustainability at all levels of education.

This article will propose answers to this question through a literature review and research in the fields of systems thinking, systems education and ESD. The aim is to achieve a better understanding of the concept of systems education and to possibly advocate a change in the current way of trying to implement ESD at all levels of education.

2. The Characteristics of Systems Thinking and Systems Education

As systems thinking and sustainability are so closely linked, it is not practical to focus on them separately [23,26,30,31]. The basic idea in systems thinking is that the world is a complex system where everything is interconnected in the form of systems with interrelated parts [32]. According to

Checkland [33], systems thinking is thinking in a holistic way, requiring that what the thinker perceives to be the whole might in fact be seen as a part of an even larger whole. Systems thinking is justified by the fact that any whole is built up by smaller wholes that exist only in relation to the complete whole [33].

Meadows and Wright [34] argue that the industrial world societies need to realize that systems thinking is not the key to prediction and control. The world is built up by complex systems and these systems are not controllable, even with the help of computers and logical data calculations. In other words, the systems can be understood in a very general way. This is because systems are inherently unpredictable. Instead, the ability to utilize the tools of systems thinking opens a world of possibilities to design and re-design systems. People must stop trying to predict and control the systems and instead learn how to dance with the systems, if we are going to find a sustainable relationship to each other and to nature.

"Systemic thinking is a mode of thinking that keeps people in touch with the wholeness of our existence" [35] (p. 282). This is a wide definition of systemic thinking or systems thinking, embracing also a spiritual level of the concept. According to Plate [36] and Monat and Gannon [37], there are a lot of well-educated members of society who have not developed the abilities and skills needed to understand complex systems. Sonnleitner, et al. [38] argue that a deep change in the educational system is necessary to enable the development of knowledge in complex systems and their systemic connections, which is crucial knowledge for a sustainable society. Additionally, Puk and Stibbards [39] highlight the importance of developing a comprehensive understanding of complex causal relationships, like the relations between natural systems and human systems might be. To develop this kind of understanding of the relation between nature and human, it is important for students to first develop an understanding of key ecological concepts. Such key concepts are the base for more complex concepts, which form the base for understanding complex relationships.

A UNESCO statement from 2005 stresses the importance as well as the problem with education: "We are faced with a paradox: Is education the problem or the solution in working toward a sustainable future? At current levels of unsustainable practice and over consumption, it could be concluded that education is part of the problem. If education is the solution, then it requires a deeper critique and a broader vision for the future." [40] (p. 59)

This statement from UNESCO calls for rethinking within the educational system. Cook [41] argues that education, as a knowledge builder at the frontier, needs continual renewal and the purpose of education must continually be redefined in learning for an unknown future. Learners must develop the capacity for realizing alternative futures. A diversity of abilities, skills, beliefs and ideas among members of society will be crucial for handling the future. To research this idea, a research project in Sydney, Australia [25] was constructed as a trans-disciplinary research project, with participating students from different disciplines and different universities working together. The project was designed to overcome the narrow boundaries characteristic for disciplines enforced through problem-based learning with a systems thinking framework using Action Research as a methodology. The researchers state that the project created "some very successful spaces for creative student engagement, which promoted deep learning and sophisticated intellectual interactions in the sustainability sphere" [25] (p. 136).

Cavana and Forgie [30], who have reviewed a series of articles within the realm of systems education and systems thinking, point out that the above-mentioned project might be the best way presented so far to teach "systems education for a sustainable planet", as Gray et al. [25] suggest in "teams". The main idea with "teams" is that if every team member is taught and understands the same shared and common "systems language, structure and methods", every team member can contribute with their strengths from various areas in working together toward shared values and objectives. If students/scientists are educated to reach the same level of "systems understanding", then scientists from different disciplines can come together, working to develop intricate models. One student cannot be expected to be an expert in all areas, but they can value their strengths and limitations working in teams with the same level of "systems understanding" to solve transdisciplinary problems [30]. "One of the reasons for using systems thinking to approach sustainability is because systems thinking is an appropriate education approach to complex problems and could provide a kind of common language for students from different disciplines" [21] (p. 3). Throughout the last decade, there have been several researchers arguing for an education with possibilities to enunciate an aim at a meta-level, advocating a kind of learning that raises awareness of social, individual, economic and environmental perspectives in a societal development [42–45]. The reasoning around systems education in this article coincides well with this demand for change in education.

These are important findings in the work ahead, as both ESD and systems thinking appear to be quite wide in their definitions and turn out to be conceptually problematic [30,37]. The intricate nature and wide definitions result in an obstacle for implementation [4].

Stave and Hopper [46] have, through a review of systems thinking literature, noted that there are seven systems thinking components that researchers seem to agree on. Moreover, Monat and Gannon [37] found through a review of key literature in systems thinking that many of the sources in systems repeat common themes. The components that Stave and Hopper [46] identify are:

- Recognizing interconnections
- Identifying feedback
- Understanding dynamic behavior
- Differentiating types of flows and variables
- Using conceptual models
- Creating simulation models
- Testing policies

The themes Monat and Gannon [37] found as common themes from their literature review and that can be directly connected to the components identified by Stave and Hopper [46] are: (1) systems thinking focused on relationships among systems components (connected to recognizing interconnections), (2) the dynamic nature of systems (connected to understanding dynamic behavior), (3) feedback mechanisms and feedback loops (connected to identifying feedback), (4) system dynamics/computer modeling (connected to creating simulation models), and (5) stock and flow diagrams as tools (can be connected to differentiating types of flows and variables). Instead of the component "testing policies", Monat and Gannon [37] found systemic root causes analysis as a very useful tool in systems thinking, which is a tool that deserves to be highlighted in this context.

If these components and common themes could form a base for "systems understanding", it would be crucial for ESD to adapt to these components and assimilate the idea of educating for the same level of "systems understanding". This would overcome the obstacles that often seem to hinder the implementation of ESD today. Examples such as teachers' lack of expertise, the intricate nature of sustainability and the interdisciplinary nature of sustainability are all found to be obstacles [4], but could be addressed through this way of thinking and working together in teams, as Gray et al. [25] propose.

If researchers could reconcile on these three points: (1) the seven components of systems thinking that Stave and Hopper [46] highlight, (2) adaptation of the thought about educating students for the same level of systems understanding and finally (3) highlight of the benefits of working in teams, it would make it easier to rethink and redesign curriculums and implement systems education promoting sustainability at all levels of education.

The next section focuses on obstacles hindering the implementation of the teaching of sustainable development. In particular, teacher education will be discussed as this is a crucial key to changing teachers' knowledge and abilities. Possible solutions and a likely way forward will be discussed, based on the idea of reconciling ESD and system education.

3. Obstacles Hindering the Implementation of Sustainable Development in Education

"It is clear that systems education, from informal learning to formal educational programs, is at the foundation of the key leverages to develop new ways of more holistic thinking to ensure systemic decision and policymaking" [21] (p. 3.).

As sustainability education is characterized by a holistic approach [47], and research [47–49] indicates that school teachers in both Finland and Sweden are not able to adapt a holistic view of education for sustainability, due to their own lack of a holistic understanding of sustainable development as a concept [7,49], systems education could be an option to consider. Similar results are found, for example, in Australia [50]. Borg et al. [49], Hofman [7], and Wolff et al. [4] state that there is a problem within teacher education when it is not able to develop the holistic thinking needed for understanding the sustainability concept.

Wolff et al. [4] recently published an article, titled "High Performance Education Fails in Sustainability?—A Reflection on Finnish Primary Teacher Education", where teacher education in the Nordic countries, and especially in Finland, is discussed. The authors point out that it is not enough to raise and write about sustainability and education in various policy documents, since there will be no change if student teachers do not receive training in sustainability education. Through their research, Wolff et al. [4] found five issues why an exceptionally good education according to the PISA (The Programme for International Student Assessment of OECD) results does not successfully integrate sustainability into the education. The obstacles are probably similar in other countries around the world that are trying to implement sustainability education in the curriculums and teacher education. It is of great importance that universities take the responsibility to promote an ESD policy; a renewed elementary school curriculum is not enough if teachers do not know how to teach about sustainability or systems thinking.

The five identified obstacles for implementing sustainability in teacher education in Finland are [4]: (1) sustainability is in conflict with overall trends in society and politics, (2) teacher education takes place at universities, (3) teacher education is based on separate academic disciplines, (4) sustainability is intricate because it is strongly connected to ecological literacy and (5) it is value-dependent. It is obvious that several of these mentioned obstacles consist of characteristics that are not only discussed in research around ESD; some of the obstacles are touched upon and can be drawn from discussions about systems education as well. Especially the last three obstacles have connections with systems education. The obstacles will be briefly addressed in a couple of separate paragraphs below.

3.1. Societal Trends and Teacher Education Take Place at Universities

Economic values and consumerism have developed to become a paradigm of our time, while world politics, first and foremost, focuses on economic growth [11–13]. The reason for our overconsumption and unsustainable way of life is not only to be found at the individual level [4]. During the past few years, policies and economies have, through joint efforts, created a growing demand for goods [4]. In Finland, education is market-oriented and has become a consumer good; education is set as a tool to achieve economic success in the world market [4]. The universities in Finland have also adapted to this market-oriented thinking and share the same values as the business sector [4]. In this market-oriented kind of education, certain kinds of knowledge are valued higher than others [31]. The education focuses on core knowledge and tests to compete with each other instead of an education that evolves values and moral responsibility [31]. Teaching student teachers about sustainability is also in conflict with this market-oriented agenda [4]. Systems thinking could be an approach that addresses these problems and makes humans more conscious about how politics, economics and consumption patterns affect our society and different systems within it.

3.2. Separate Academic Disciplines

Unfortunately, universities often have a very conservative approach with strong subject orientation, where interdisciplinary research is still seen as challenging [4]. As such, sustainability is very hard to implement in higher education because of its interdisciplinary nature. For example, teacher education in Finland is based on separate academic disciplines and a traditional school curriculum [4], which is problematic regarding the importance of a holistic understanding of sustainability to develop new perspectives in education [17]. Christie et al. [51] argue that the slow implementation of sustainability in higher education is due to both the complexity of sustainability and epistemological differences between disciplines. An interdisciplinary meta-knowledge for solving sustainability problems is asked for [52]. Wolff et al. [4] argue that it is crucial that institutions offering teacher education regard sustainability as an important topic, but they also note that it is not enough for these kinds of educational institutions to write about sustainability in their policy documents and strategies. They call for a transdisciplinary implementation in teacher education involving both teachers, university leaders and students from different disciplines.

Similar issues are present in the research experiment conducted by Gray et al. [25] solving sustainability issues through problem-based learning with a systems thinking approach and action research as the methodology. Within the research experiment, transdisciplinary issues were solved by working together in teams. Working in teams may also affect the intricate nature of sustainability, for example, if team members from different disciplines come together working within their own strengths, sharing knowledge and information within the team.

Wakeland [53], Ison and Blackmore [22], Salīte et al. [20], Gray et al. [25], and Kordova et al. [21] connect systems education with transdisciplinary learning. Wakeland [53] states that systems science is best described as transdisciplinary. Weber [54] also emphasizes the complexity and separate two interlinked dimensions, one with a focus on the planet Earth and the other with a focus on human societies. All of these claims demonstrate the transdisciplinary nature of sustainability and systems thinking offered by Kordova et al. [21] as an adaptable approach toward sustainability, as systems thinking is useful in complex problem-solving.

This reveals the impact an implementation of systems thinking or systems education could have on teacher education. It would require teacher education to transform from an education based on separate academic disciplines to a transdisciplinary education.

3.3. The Intricate Nature of Sustainability

The intricate nature of sustainability has already been discussed earlier in this paper. However, the reason why it is found to be that intricate is mainly due to its strong connection to ecological literacy [4,27,55]. During the last 20 years, people's knowledge and understanding of ecological key concepts have decreased [56–59] and a kind of ecological illiteracy has developed [39,60,61]. Puk and Stibbards [39] argue that one of the important things for students to develop during their studies is an understanding of key ecological concepts, so they can learn to understand the complex relation between human systems and systems in nature. The escalating development of ecological illiteracy implies that key ecological concepts are not addressed during elementary school, secondary school or higher education. Apparently, key ecological concepts are not addressed in the Nordic teacher education, either [27,56]. Systems thinking has been raised in this article as an extremely good approach to solving intricate problems through action-based teamwork. For example, Kordova et al. [21] argue that the reason to approach sustainability through systems thinking is because systems thinking is a suitable educational approach to complex problem-solving. Monat and Gannon [37] also highlight the great power of systems thinking in solving complex problems.

This reveals that the intricate nature of sustainability could be seen as less complicated through a development and adaption of systems thinking.

3.4. Value Dependent

As sustainability is a concept involving values [4,23,27,31,62] ethics and morals [4,31,62], it is a demanding topic to teach and is dependent on talented teachers [63]. Teachers do not become talented in these areas without adequate training [4,27]. The already highlighted issue of a market-oriented kind of education that embraces certain kinds of knowledge is also problematic regarding abilities to develop values and morality within students [31]. An ethically conscious teacher education is needed to develop an ethical consciousness within student teachers and to develop their ability regarding ethical deliberation, value discussions and to understand ethical sustainability issues like global equity, fairness and responsibility [4]. Systems thinking and teamwork could be an excellent tool in developing this kind of ethical consciousness.

4. Discussion and Conclusions

As research indicates, an ecological illiteracy has developed during the past few decades. Our planet suffers from overconsumption and an unsustainable way of life. In addition, this unsustainable way of life does not even seem to benefit our wellbeing. It appears obvious that there is something wrong in our system and our way of thinking. UNESCO calls for a change in how we think and act, but how do we manage this change? To enable this change, UNESCO places education in a key position, but so far, the desired results have not been achieved, even though ESD has been on the agenda for more than a decade. Perhaps ESD is not enough; possibly there is something still lacking that is crucial for a change to start.

The similarities in the nature of ESD and systems education are crystallized in this literature review. Some of the articles that have been reviewed agree that the required areas for sustainability are systems thinking, an action approach and teamwork. There are indications that ESD and systems education could benefit from each other. Systems education and ESD could obviously constitute an interlinked common ground for sustainability education throughout the world, instead of being bounded from each other.

This new learning approach with systems thinking linked to ESD could emphasize the development of different levels of systems understanding, such as learning how to work in transdisciplinary teams, teaching basic ecological key concepts and promoting value discussions, deliberation and action competence. It would now be extremely important to conduct more experiments and further research around this potential learning approach, in order to determine whether this is the optimal way to approach education for sustainability. As such, it could thus be stressed as being one of the most important changes to implement as quickly as possible, at all levels of education.

The main focus where change is very crucial is within teacher education. All newly qualified teachers could adapt to this new educational approach, especially as research indicates that the implementation of sustainability and systems thinking in Nordic teacher education has failed. In the work forward towards sustainability, teacher education institutions would need to emphasize both sustainability and systems thinking to a greater extent than now. A complete rethinking of teacher education would be preferable, but that would require a complete reorganization and very devoted leaders of the institutions.

Components that would be crucial to embed in teacher education for the student teachers to achieve a systems thinking knowledge base are listed below. It would be of great importance that all teacher students develop a systems thinking perspective, so the newly qualified teachers can teach systems thinking skills to children for a sustainable future.

- Recognizing interconnections
- Identifying feedback
- Understanding dynamic behavior
- Differentiating types of flows and variables

- Using conceptual models
- Creating simulation models
- Testing policies
- Knowledge about systemic root cause analysis

Beyond this change, teacher education should also adopt an action competence approach and highlight the importance of didactics underpinning the development of student teamwork. This approach enables students to learn from each other, particularly when every team member works from their own strengths in complex problem-solving. However, this kind of change is time-consuming. Adding some compulsory courses on the concepts of sustainability, ecological principles and systems thinking for all teacher students could serve as a stopgap, but in the long run, a reorganization of teacher education institutions toward a systems- and action approach for solving complex sustainability problems would be preferable.

In countries where teacher education institutions are not autonomous, as it is for example in Finland, governments can take action to promote the reorganizations needed for ESD and systems thinking to be implemented in teacher education. However, in countries where the teacher education institutions are autonomous, this kind of reorganization and change is dependent on the university leaders' interest. Finally, some suggestions are provided in the form of a list for facilitation of the recommended changes.

4.1. Governmental Regulated Teacher Education Institutions

- Investigate all teacher education institutions in the country: how is ESD implemented right now?
- Review the curricula of primary schools regarding implementation of ESD.
- Make changes in the laws regulating teacher education and primary schools if found necessary to promote ESD and systems thinking.
- Provide in-service training in both ESD and systems thinking for teachers educators at all teacher education institutions and for teachers in general education.
- Add compulsory courses on the concepts of sustainability, ecological principles and systems thinking for all teacher students.

4.2. Autonomous Teacher Education Institutions

- Even though teacher education institutions might be autonomous, there are often some performance agreements between a country's ministry of education and the institutions providing teacher education. It is here the government that can set higher requirements to promote ESD and systems thinking in teacher education.
- A ministry of education should gather all leaders of teacher education institutions to educate the leaders in systems thinking and ESD issues to awake the leaders' interest in these issues.
- If institution leaders' interest in ESD and systems thinking can be evoked, a total reorganization of teacher education could be possible.
- The components mentioned earlier in this section that would be crucial to embed in teacher education for the student teachers to achieve a systems thinking and ESD knowledge base would be possible to implement in teacher education if the leader of the institution is prepared to work for reorganization.

These suggested action items that could be taken by governments and universities to facilitate the recommended changes are purely general suggestions but they could be quite fruitful. Further research on reorganization of teacher education is needed and this will be the topic of a follow-on paper.

Funding: This research received no external funding.

Acknowledgments: This article is dedicated to Hannu, a very dear friend of mine that died in a tragic accident during this writing process. Hannu was a big part of my system "living with" and "doing things for others". Now a very important part in the system is missing, both for me and for 22 young soccer girls who we coached together. Thank you, Hannu, for your wisdom; you taught me a lot.

Conflicts of Interest: The author declares no conflicts of interest.

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Article

Conceptualizing Shadow IT Integration Drawbacks from a Systemic Viewpoint

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Received: 30 October 2018; Accepted: 29 November 2018; Published: 3 December 2018

Abstract: Business units are increasingly able to fuel the transformation that digitalization demands of organizations. Thereby, they can implement Shadow IT (SIT) without involving a central IT department to create flexible and innovative solutions. Self-reinforcing effects lead to an intertwinement of SIT with the organization. As a result, high complexities, redundancies, and sometimes even lock-ins occur. IT Integration suggests itself to meet these challenges. However, it can also eliminate the benefits that SIT presents. To help organizations in this area of conflict, we are conducting a literature review including a systematic search and an analysis from a systemic viewpoint using path dependency and switching costs. Our resulting conceptual framework for SIT integration drawbacks classifies the drawbacks into three dimensions. The first dimension consists of switching costs that account for the financial, procedural, and emotional drawbacks and the drawbacks from a loss of SIT benefits. The second dimension includes organizational, technical, and level-spanning criteria. The third dimension classifies the drawbacks into the global level, the local level, and the interaction between them. We contribute to the scientific discussion by introducing a systemic viewpoint to the research on shadow IT. Practitioners can use the presented criteria to collect evidence to reach an IT integration decision.

Keywords: shadow IT; IT integration; IT integration drawbacks; application integration; path dependency; path biography; switching costs

1. Introduction

Digitalization describes the introduction and usage of digital technologies in a social, individual, and organizational context [1]. In 2018, a survey of 3958 information technology (IT) leaders revealed that 61% see higher revenue growth than their competition when using digital technologies [2]. To achieve competitive advantage through digitalization, organizations have to massively transform their organizational structures, strategies, methods, business models, and enterprise architectures [1]. In the past, the implementation of new IT was mainly the task of the organization and the IT department; nowadays, user-friendly IT allows business units to shape digitalization [3]. If the business unit implements a new IT system on its own without a central IT department being involved during the development or the subsequent control, the phenomenon is called shadow IT [4]. The effect of shadow IT on the enterprise architecture of an organization has two perspectives: On the one hand, shadow IT introduces innovation into an organization and allows a higher flexibility for business units [5,6]. On the other hand, inefficiencies occur [7]: The heterogeneity rises, because business units choose technology on their own. Complexity increases, because shadow IT is connected or exists parallel to formal systems. Integration, by linking or unifying shadow IT and the redundant enterprise system, could eliminate redundancies and solve associated problems [8]. A survey of 490 CIOs revealed that 64% regard IT integration as a priority, while simultaneously desiring a high degree of innovation and flexibility in the IT architecture of their organization [9]. Thereby, organizations find themselves in an area of conflict, as IT integration might eliminate the benefits that shadow IT offers [10]. Because organizations must be aware of these drawbacks before performing an IT integration, this paper aims at presenting a framework for shadow IT integration drawbacks.

Most studies on IT integration focus on the benefits and provide classifications for its factors [11]. Research on IT integration drawbacks focuses merely on monetary factors such as indirect and direct costs [12,13], or states that some integration technologies are more expensive than others [14,15]. Research on non-monetary factors considers IT integration barriers in environments such as hospitals [16] or governments [17] or for special methods like enterprise application integration (EAI) [15,18]. Thereby, none of these studies focus on the phenomenon of shadow IT [11]. Additionally, IT integration research in general lacks a link with the existing theory base [19]. Therefore, this paper contributes to the scientific discussion as it presents a theory-based view of shadow IT integration drawbacks using the systemic theories of path dependency and switching costs. Besides, practitioners can use the resulting framework to assess the drawbacks when coming to a decision on shadow IT integration.

The paper is structured as follows: At first, we introduce the problem that shadow IT causes in the enterprise architecture. Then, we illustrate our research approach consisting of our systemic theory base and the literature review that we conducted. Afterwards, we present the results and discuss them. Finally, we provide a conclusion and note possible future research directions.

2. Shadow IT in the Enterprise Architecture

Shadow IT describes IT systems that business units implement individually in their business processes, whereby they are not involved in an organizational IT management [20]. On the one hand, it has technological aspects because shadow IT occurs in various forms, such as local applications, spreadsheets, end devices, cloud services, or combined solutions [5], and needs technical support to function in an organization [6]. Yet, shadow IT also has social components because business employees are highly involved during its implementation and usage [21,22]. Therefore, we regard shadow IT as a socio-technical phenomenon [4].

In the beginning, shadow IT is often experimental and small, as it responds to an emergent need in the business unit [5,22]. Once established in the organization, shadow IT can grow large because business units share the benefits that the system provides for them [23]. Due to inertia on an individual as well as an organizational level, business users continue using shadow IT [22]. Thereby, it often gets intertwined with the enterprise architecture of an organization [24]. Shadow IT reinforces by emerging and reemerging in a cycle of time and cost pressures [4]. Thereby, it shapes the enterprise architecture and can become an important part of it [25]. Shadow IT exists alongside formal enterprise systems and either complements, expands, or supplements them [26]. Studies show that a redundancy of data or functionality exists in a majority of the cases [26], and that as a result shadow IT causes various inefficiencies in the enterprise architecture [7]: First, IT departments often do not know about shadow IT, which leads to an non-transparent enterprise architecture, the inability to manage it, and related risks. Second, responsibilities are often unclear, which reduces business-IT-alignment. Third, shadow IT increases the complexity of the enterprise architecture in various ways. The low standardization and integration and high heterogeneity prevent automation [10] and thereby hinder digitalization [27].

Organizations can solve these inefficiencies by converting shadow IT into business-managed IT. Thereby, they identify and include shadow IT in IT management [5,28]. However, redundancies of shadow IT and enterprise systems will remain, and organizations must take architectural measures to solve them. IT integration is an established concept to cope with these types of problems [16]. A common database or data interface can solve data redundancies, and a unification of shadow IT and the redundant enterprise system can remove functional redundancies [8,29].

Like in other IT integration decisions [30], organizations must valuate drawbacks and benefits of an integration of shadow IT and the redundant enterprise system. While many studies analyze IT integration benefits, no study discusses the drawbacks [11]. Some studies provide a classification based on direct costs, such as the implementation of the IT integration, and indirect costs such as training of employees [12,13]. Others compare different costs for different integration technologies, such as interfaces and unification of systems [14,29] or methods such as EAI versus point-to-point integration [17,31]. A discussion of non-monetary costs exists in the analysis of IT integration barriers. Here, research presents barriers that can occur during integrating systems, such as resistance to change [18] or technical incompatibility [32]. Overall, research lacks a synthesis of the discussions on monetary and non-monetary costs and a theory-based specification of these drawbacks to the phenomenon of shadow IT. Shadow IT research has started to target integration by pointing out redundancies [26] or providing evidence based on a small number of cases [27]. None of the research on shadow IT integration has presented a theory-base yet, and IT integration research lacks that in general [19]. Additionally, existing research on IT integration focuses on the benefits of an IT integration [11]. By providing a theory-based synthesis of the drawbacks, we can close this research gap. As a result, organizations can weigh the drawbacks against the benefits to come to an integration decision of shadow IT and enterprise systems. To be able to achieve this goal, we pose the following research question: Which drawbacks do organizations face when deciding about the integration of shadow IT and an enterprise system?

3. Research Approach

To answer our research question, this section first presents our theory background. Then, we show our research method that led to the conceptual model that we present in the next section.

3.1. A Systemic Viewpoint on Shadow IT Integration: Path-Dependency and Switching Costs

Path dependency is a concept introduced from evolutionary economics and explains occurring inefficiencies in a complex system from a systemic viewpoint [33]. Coming from the discussion on economical processes, the theory explains that historic choices of technology combined with several types of self-reinforcing effects, such as economies of scale, emotional reactions, or political processes that lead to increasing returns and the establishment of a dominant design [34]. However, after the dominant design has been established, markets may reside in an inefficiency, where a seemingly less appropriate solution has the greatest market share although other solutions might be technologically more appropriate [34]. In this inefficient state, users can no longer freely switch to another technology, but find themselves in a lock-in with the current dominant technology [33].

In this lock-in situation, the costs to switch to another technology are very high due to the high intertwinement of the technology with the organization [35]. These so-called switching costs are originally defined as “onetime costs that customers associate with the process of switching from one provider to another” [36], but are also applicable for switching technologies in an organization [35]. Switching costs are not only monetary costs but also include emotional or cognitive costs, such as the search for a new technology; learning; transaction costs; and costs due to loyalty, habit, and emotion [37]. Burnham categorizes eight switching costs into financial, procedural, and emotional types of switching costs using factor analyses on a survey on perceptions of 144 customers to change their service provider [36].

Information systems research increasingly recognizes that path-dependency is a relevant concept in the field of enterprise architecture [35,38] and suggests that it is an important theory base for the research field of IT integration [19]. We assume that path-dependency is suitable to shed light on the specific problem of shadow IT due to the following reasons: the last section explained that various effects lead to the intertwinement of shadow IT with the organization [4,23], and the high involvement of business users during its implementation and usage [21]. This points to self-reinforcing effects that affect the evolution of the enterprise architecture and switching costs that arise. Often, shadow IT even becomes an important part of the enterprise architecture [24]. In these cases, the historic choice of shadow IT implementation can lead to various inefficiencies in terms of transparency, redundancy, and governance in the enterprise architecture, where organizations find themselves with resulting problems such as missing automation, regulatory requirements, data integrity, and unclear responsibilities [26]. These facts suggest that the self-reinforcing effects can even lead to a lock-in with the existing shadow IT.

In cases where the lock-in and the occurring inefficiencies stem from the redundancy of the shadow IT with the enterprise system, organizations can integrate the two systems [8]. Thereby, business units must change from using the old shadow IT to using the new, integrated system. Thereby, they must adapt their work routine. We therefore regard the transition of the old system to the new system as a switch and apply the concept of switching costs to assess the shadow IT integration drawbacks.

3.2. Research Method

Because IT integration is a mature topic with an existing body of research [19], we used a literature review to develop our conceptual model [39]. A lot of the conducted research in the field is done as case study research or practitioner surveys [19], which assure that our study is also practically relevant. Additionally, our research method needed to reflect the fact that shadow IT is a socio-technical phenomenon [4]. Therefore, we chose the Path Biography Method (PBM) to conduct the analysis in our literature review [40]. The approach of the PBM goes beyond the mainly quantitative-empirical methods of IS research focusing on technical aspects [41] as well as the management research that mainly concentrates on organizational aspects [42]. Rather, the PBM integrates both aspects of our research problem [40]. Additionally, it is useful for research areas that span disciplinary boundaries [40] and, although it is a fairly recent method, research suggests that it is relevant in the area of IT integration [43].

Figure 1 shows our research method. Our literature review consisted of a structured literature search and the analysis, where we used the PBM to conduct the coding.

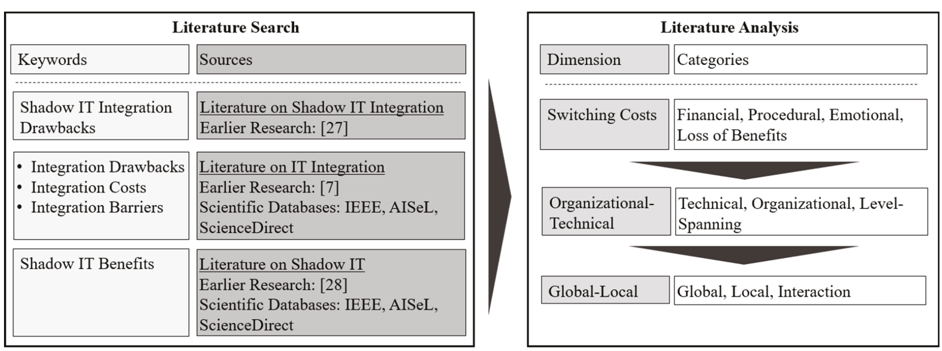

Figure 1. Research Method.

The first step in our research procedure was the collection of possible shadow IT integration drawbacks from shadow IT integration literature. Research on this specific topic is scarce and has covered its drawbacks only briefly [11]. Therefore, we expanded our search to literature on IT integration in general. Thereby, we consulted an existing review on IT application integration [11] and complemented these findings by a search on literature starting from 2017 on using the keywords *integration costs*, *integration barriers*, or *integration drawbacks* in title or abstract in the databases of IEEE, AISeL, and Sciencedirect. Additionally, because possible drawbacks from integrating shadow IT mainly stem from its loss and the following loss of its benefits [27], we scanned a former review on shadow IT on literature of shadow IT benefits [28]. We complemented this review by conducting a literature search in IEEE, AISeL, and Sciencedirect using the keywords *shadow/feral systems*, and *shadow/grey/hidden/rogue IT* in combination with *information technology/services/systems/security*, in title or abstract from 2017 on. After we finished the literature collection, we scanned it for specific drawbacks, excluded those that made only vague or relative statements or did not mention any specific factors, and in the end, removed duplicates.

In a second step, we used an approach of coding [44] to assign the found criteria to pre-set codes following three sub-steps: First, we used the concept of Burnham that divides switching costs into procedural, financial, and relational costs [36]. Principle 1 of the PBM requires one to focus on the self-reinforcing effects that cause the inefficiency [40], which is, in our case, the redundancy of shadow IT and the enterprise system. To adapt the model to this specific situation and make it valuable for shadow IT research, we added a fourth cost category that accounts for the loss of shadow IT benefits. Second, to comply with principle 2 of the PBM, we additionally differentiated between the technical, organizational, and level-spanning drawbacks. Third, we mapped them to the local level, the global level, or the interaction of the levels following the third principle of the PB. Thereby, our knowledge from shadow IT literature and the fact that most of the literature was practical case study research helped us to evaluate the criteria on a fit to the specific phenomenon of shadow IT integration. One author conducted the analysis and discussed the results with the other authors. In several iterations, we thereby refined and evaluated the criteria and their mapping. As a result, a three-dimensional framework of shadow IT integration drawbacks emerged that we will present in the next chapter.

4. Results

This chapter discusses the findings from the literature search and the first step of the literature analysis. Afterwards, we present the results with a focus on the second and third step of the analysis.

4.1. Findings from Literature Search

The first step in our literature search was the search in the research field of shadow IT integration. Hereby, as expected due to the topic being not very well covered, only one study emerged. Second, we searched the literature on IT integration. Relying on an earlier literature review [11], we collected 14 studies.

From the additional search in the scientific databases, we only collected one more study, because the others did not mention specific cost dimensions. Vague statements regarding costs are rather common in this field of study [19]. Last, we consulted the literature on shadow IT. Based on an earlier review [28], we collected seven relevant studies that mentioned specific shadow IT benefits. The additional search in the databases resulted in two more studies. In total, after removing duplicates, we collected 25 studies (Table 1).

Table 1. Results of Literature Search.

		Literature on Shadow IT Integration	Literature on IT Integration		Literature on Shadow IT	
	Sources	[27]	[7]	IEEE; AISeL, ScienceDirect	[28]	IEEE, AISeL, ScienceDirect
IT Integration Costs	Found Studies	1	13	38	0	0
	Relevant	1	13	1	0	0
IT Integration Barriers	Found Studies	1	17	3	0	0
	Relevant	1	13	0	0	0
IT Integration Drawbacks	Found Studies	1	0	2	0	0
	Relevant	1	0	0	0	0
Shadow IT Benefits	Found Studies	1	0	0	44	15
	Relevant	1	0	0	7	2
Sum (unique, relevant)		1	14	1	7	2
Total				25		

4.2. Shadow IT Integration Drawbacks

The second step in our research process was the analysis of the literature using the principles of the PBM. As a result, we found three different dimensions of shadow IT integration drawbacks: the switching cost dimension consisting of the procedural, financial, and emotional drawbacks [36], as well as the loss of shadow IT benefits from the shadow IT literature. The second dimension is the organizational-technical dimension and the third dimension the global-local dimension.

4.2.1. Analysis from a Switching Cost Dimension

We assigned the found drawbacks to the four pre-set codes: financial, procedural, and emotional switching costs, and loss of shadow IT benefits. Table 2 shows the results of our coding and the corresponding sources. This sub-section focuses on the switching cost dimension but also gives reasons why we included them in the context of shadow IT integration.

Table 2. Result of Coding of Integration Drawbacks to the Switching Costs Dimension and Sources.

Pre-Set Codes: Costs Dimension	Properties: Integration Drawbacks	Sources
Financial: Financially quantifiable resources for	hardware	[12,13,18]
	software	[12,13,18]
	development/adaption	[12,13,17,18,30,32,45]
	maintenance	[13,15]
	external support	[12,13,18]
Procedural: Expenditure of time and effort for	project coordination	[12,15,45,46]
	employee training	[12,13,15,18,30,45,46]
	technology understanding	[12,16,47–49]
	top management support	[12,13,18,45]
	organizational restructuring	[13,18,30]
	process understanding	[12,13,15,18,30,45,46]
	communication	[12,13,18,45,46]
	changing culture	[12,13,15,18,30,45,50]
Relational: Psychological or emotional discomfort due to	sharing data	[18]
	using technology	[12,13,30]
	losing power	[13,18,30,45,49]
Loss of shadow IT benefits: Losing former	innovation	[5,6,51–54]
	flexibility	[5,27,55]
	productivity	[5,22,27,56]

The first factor in the switching cost dimension is financial expenditures that are "financially quantifiable resources" [36]. Those expenditures are monetary drawbacks, such as expenditures for integration hardware, software [12,18] mentioned by a few studies, or the initial adaption of the integration technology to the needs of the organization referred to by more than half of the studies [17,32,45]. Additionally, some include the costs that the maintenance of an IT integration causes [13,18]. Because shadow IT occurs in various forms [5], the monetary drawbacks for implementation, development, and maintenance also differ. Additionally, we include the external support. Although only one source mentioned this factor explicitly [12], depending on the integration technology, organizations might need external support to find suitable integration technology as well as to adapt it. Although the organization also must spend time and effort on the search and the coordination, the resources that the support needs are financially quantifiable.

Some drawbacks consist mainly of the procedural switching costs, which are "expenditures of time and effort" [36] that they cause. Factors included in this category are the employee training as well as the project coordination. Project coordination includes the time of the project team in general [12], but also the effort of coordination between departments [17] or the planning of the process and the needed resources [46]. Depending on which technology the organization has chosen to integrate the shadow IT with the enterprise system, those expenditures may vary as well. Some studies stress that the organization has to understand [47,49] and then select the right integration technology [12,48]. Besides, research mentions that the organization also has to understand the process behind IT integration, which requires time and effort [15,18]. Additionally, top management support is very important [12,13], and the organization also, in some cases, has to restructure their processes [18,30] and communicate the change [46]. Those factors, again, also concern shadow IT integration. Most studies mention *culture change* as important. This includes changing the culture [13,18] due to the resistance to change that it causes in members of the organization [15,46]. Given the high involvement of business units during the lifecycle of shadow IT [4], we assume that this factor is especially relevant for shadow IT integration.

Relational switching cost, the "psychological or emotional discomfort" [36], is the third category. Factors that cause relational switching costs are sharing data [18] and using the new technology [12,30]. Losing power is an organizational factor that causes discomfort in certain members of an organization [18,49]. This factor might be especially relevant, because shadow IT research focuses on it as well [4,57].

The fourth category of switching cost is the loss of shadow IT benefits. Thereby, we found three important factors. Shadow IT is often innovative, in terms of processes or even technology [6,52,54]. An IT integration might eliminate this innovation if done with few considerations [10]. Another factor is the productivity that increases in a lot of cases [5,22,56]. Depending on how the organization handles the IT integration, this productivity increase might get lost. As a last factor we mention the loss of flexibility. Business units are able to adapt their solution to changing needs very easily [27,55]. An IT integration might eliminate the ability to adapt the solution in an easy and flexible way.

4.2.2. Analysis from an Organizational-Technical Dimension

Besides allocating the integration drawbacks to the switching cost dimension, we also analyzed them on the organizational-technical dimension (Table 3). Thereby, the organizational aspect of shadow IT integration comprises mainly the business unit and its interaction with the system and the avoided enterprise system [4]. Factors that we included here because they are mainly organizational are external support; the top management support; the organizational restructuring; the cultural change; as well as the loss of power, flexibility, and productivity.

Table 3. Result of Coding of Integration Drawbacks to the Organizational-Technical Dimension.

Pre-Set Codes: Organizational-Technical Dimension	Properties: Integration Drawbacks
Drawbacks from Organizational Change	External Support Top Management Support Organizational Restructuring Process Understanding Communication Cultural Change Losing Power Losing Flexibility Losing Productivity
Drawbacks from Technological Change	Hardware Software
Drawbacks from Level-Spanning Activities	Development Maintenance Project Coordination Employee Training Technology Understanding Sharing Data Using Technology Losing Innovation

The technical aspect focuses on the shadow IT technology and its support structures [4]. Here, we associate the monetary factors of the hardware and software.

In other factors, the organizational and the technical aspects are intertwined and a differentiation between the two aspects is hardly possible. Hereby, we assign the development and maintenance of the integration technology, which depends both on the technology but also on the developers [18]. We also included project coordination, because one source mentions the influence of tooling during this task [46]. The employee training and technology understanding both depend on the actors as well as on the technology. Sharing data and using the technology are discomforts that stem both from the user and the integration technology [12,30]. Losing innovation can have an organizational aspect if it comprises process innovation, but also a technical aspect if it involves the introduction of new technology [54].

4.2.3. Analysis from Global-Local Dimension

The third analysis of the shadow IT integration drawbacks focuses on the global and the local level of influence (Table 4). In our analysis, the global level is comprised of the organizational IT management that is responsible for IT integration, often represented by the IT department. Here, we assign the tasks of the project team, which are project coordination [46], technology understanding, organizational restructuring, and process understanding [12]. Top management support is required from the management of the organization [45] and is therefore also a global factor. The loss of innovation is also a factor on the global level, because shadow IT technology is innovative for the whole organization [54].

Table 4. Result of Coding of Integration Drawbacks to the Global-Local Dimension.

Pre-Set Codes: Global-Local Dimension	Properties: Integration Drawbacks
Drawbacks in the IT Department/Organization	Project Coordination Technology Understanding Top Management Support Organizational Restructuring
Drawbacks in the Business Units	Sharing Data Using Technology Losing Flexibility Process Understanding Losing Innovation
Drawbacks for the Interaction of Both Levels	Hardware Software Development Maintenance Employee Training External Support Communication Cultural Change Losing Power Losing Productivity

In our analysis, the local level represents factors that primarily affect the business unit. This is, because it is a crucial actor in the context of shadow IT [4]. One important factor is the culture change that the business unit must undergo due to a new technology [13]. Additionally, they experience discomfort through sharing data [18] and using the technology [12]. Also, business units might lose flexibility in their work routine due to IT integration [55].

We assign some factors to the interaction between the two levels. Expenditures for hardware, software, development, and maintenance of the solution might occur on the global but also on the local level. Who pays for the IT integration depends on the cost structure of the organization but also on the negotiation between the IT and the business department. Employee training is a factor that occurs on both levels. The IT department needs training to understand the integration technology [18], and the business unit needs training to use the technology [12]. Additionally, either the IT department might lose power [13,57] or the business unit [4]. Losing productivity also occurs on both levels, because while the business department loses productivity in their daily work, this productivity loss also affects the productivity of the whole organization [27].

4.3. Conceptual Framework for Shadow IT Integration and Discussion

Given the results of our literature analysis, we can reply to our proposed research questions: Which drawbacks do organizations face when deciding about the integration of shadow IT and an enterprise system? Figure 2 summarizes these findings, including the assignment of each factor to the three different dimensions: the switching cost dimension, the organizational-technical dimension, as well as the global-local dimension.

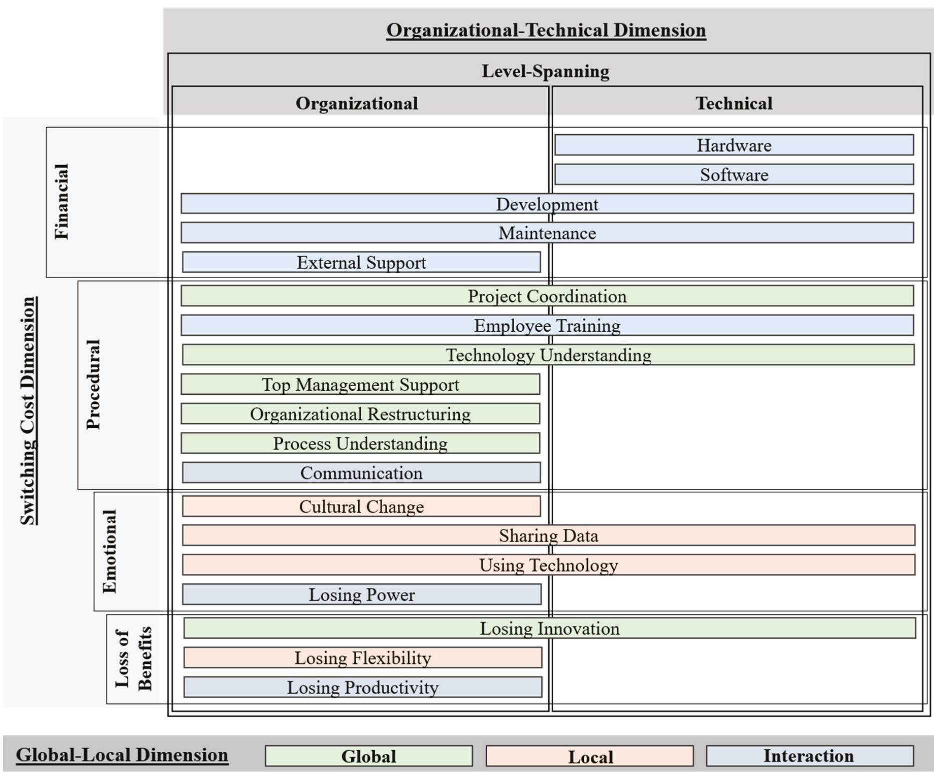

Figure 2. Shadow IT Integration Drawbacks—Conceptual Framework.

Our framework presents an overview of the 19 different factors that organizations must consider when integrating shadow IT with redundant enterprise systems. It integrates prior studies on integration costs and integration barriers. Additionally, it enhances and specifies then to the particularities of shadow IT. Thereby, it adds a theory base to IT integration research [19]. With the framework, organizations can first assess for each of the shown factors whether it is existent in their IT integration case or not. Second, organizations can use the framework to derive the impact that the relevant factors have. The visual representation allows organizations to consider multiple dimensions at the same time. Thereby, it enables organizations to keep an overview about the different aspects that influence the factor and to target it accordingly.

From the switching cost dimension, they can identify whether the factor consists of monetary or non-monetary aspects [36]. A financial factor implies that organizations must assess the costs and include them in their budgeting processes. However, our framework shows that most of the drawbacks are not purely monetarily driven. Therefore, organizations should pay the same attention to each of the other three categories. A procedural factor indicates that organizations must identify the time of involving relevant stakeholders during the integration project. Afterwards, they must observe it in their resource planning. Change management is important, as it is a complex task that organizations must plan and execute carefully in a timely manner. An emotional factor highlights the existence of specific fears, which organizations need to address during their communication and change management. The introduction of the fourth category of drawbacks targets the particularities of shadow IT [11]. A loss of benefits has an impact on the choice of the integration technology, which should allow the flexibility for the business unit or keep the innovation. As a result, organizations align with the requirements of digitalization [1].

This overview of the organizational-technical dimension helps organizations to manage the social processes during the IT integration process [40]. Our framework indicates that the organizational aspect is as important or even more important as the technical one, given the number of factors that we assigned to the organizational side. This notion confirms prior research on the emergence of shadow IT [22] and stresses that organizations have to observe and manage the social and organizational processes.

The global-local dimension is especially important in shadow IT integration. Prior studies indicate the importance of the business unit that implements and maintains the shadow IT [4]. Our framework helps to keep in mind the actors on the different levels and enables organizations to target them with the right IT integration measures. Our results indicate that the global tasks of the IT department mainly consist of managing the IT integration process. However, most of the overall tasks occur in the interaction between the two levels. This points at the importance of the coordination and cooperation between the IT department and the business unit, which has been already pointed out by past research [5,22]. Thereby, it stresses the role of the business units and encourages organizations to actively seek and monitor their opinion toward possible IT integration.

5. Conclusions and Future Research

The goal of this paper was to present a conceptual framework of shadow IT integration drawbacks. To reach this goal, we conducted a literature review on IT integration costs and barriers but also on shadow IT benefits to be able to capture the particularities of shadow IT. As a result, we developed a framework of shadow IT integration drawbacks based on the concept of switching costs in the context of path dependency. The framework is multi-dimensional and includes organizational-technical factors as well as factors of global and local influences.

Practitioners can use our framework during the process of deciding whether to integrate shadow IT and an enterprise system. They can collect evidence following the presented criteria. The switching cost dimension helps to identify what type of drawback a specific factor causes, which organizations can then target using financial resources, change management, planning of resources, and choosing the right integration technology. The global-local perspective helps to identify and target the appropriate stakeholders.

We theoretically contribute to IT integration research by integrating the research streams of costs and barriers. Additionally, we enhance the research on shadow IT that can use this framework when coming to an IT integration decision. Besides, research can benefit from our framework to tackle the problems of digitalization that have to weigh letting business units innovate and integrating IT systems for data integrity in the enterprise architecture. Furthermore, the framework is based on the concept of path dependency and introduces this theory in the context of an IT integration decision.

Certain limitations are also present in our research upon which future research can be based. First, the framework presents factors but no measurement for these factors. Therefore, further studies may provide a measurement. Second, although based mainly on literature on case study research, the framework is only conceptual. It has not been evaluated in practice, which should be a focus of future research. Third, to come to an IT integration decision, the drawbacks must be integrated with the benefits of shadow IT integration. Future studies might develop a framework that includes the benefits as well as the drawbacks to gain a holistic view of shadow IT integration.

Author Contributions: M.H., C.R., S.Z. and C.F. are all part of the research project. M.H. performed the literature search and the analysis. S.Z., C.R. and C.F. reviewed and refined the analysis. M.H., S.Z., C.R. and C.F. mutually discussed the results as well as the scientific contributions and determined the structure of the research paper. M.H. wrote the paper and consulted S.Z., C.R. and C.F. regularly to receive their feedback on the structure and the content of the current status.

Funding: This research received no external funding.

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

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Systemic Semantics: A Systems Approach to Building Ontologies and Concept Maps

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Received: 31 March 2018; Accepted: 24 July 2018; Published: 10 August 2018

Abstract: The field of systemology does not yet have a standardised terminology; there are multiple glossaries and diverse perspectives even about the meanings of fundamental terms. This situation undermines researchers' and practitioners' ability to communicate clearly both within and outside their own specialist communities. Our perspective is that different vocabularies can in principle be reconciled by seeking more generalised definitions that reduce, in specialised contexts, to the nuanced meaning intended in those contexts. To this end, this paper lays the groundwork for a community effort to develop an 'Ontology of Systemology'. In particular we argue that the standard methods for ontology development can be enhanced by drawing on systems thinking principles, and show via four examples how these can be applied for both domain-specific and upper ontologies. We then use this insight to derive a systemic and systematic framework for selecting and organising the terminology of systemology. The outcome of this paper is therefore twofold: We show the value in applying a systems perspective to ontology development in any discipline, and we provide a starting outline for an Ontology of Systemology. We suggest that both outcomes could help to make systems concepts more accessible to other lines of inquiry.

Keywords: concept map; termbase; systems perspective; ontology of systems; worldview; frontier research

1. Introduction: Glossaries and Ontologies in the Context of Systemology

Systemology is a field with a rich variety of important concepts but no standardized way of expressing them. One of the most important terminology resources in the field is Charles François' *International Encyclopedia of Systems and Cybernetics* (hereafter, '*Encyclopedia*') [1], with fully 3800 entries. It is an encyclopedia though, not an ontology, which means terms may have multiple definitions. In fact, this manifests *in extremis*: the *Encyclopedia* contains 18 pages of definitions for the term 'system' and nearly four pages of definitions for 'hierarchy'.

In the absence of an agreed terminology for the field, and perhaps also because the *Encyclopedia*'s cost puts it out of reach of many systemologists, individuals will often develop vocabularies for how they use systems terms in their own work. If explicit, these may be published as glossaries to their books or papers, e.g., [2] (pp. 21–33), [3] (pp. 11–46), [4] and [5] (pp. 13–68), [6] (pp. 353–360), and [7] (pp. 205–212). However, those who do this rarely use formal methods or develop any structure for their terminologies, and their term use is often inconsistent with that of other researchers, even within the same community. Readers are left to try to rationalise different meanings across the resources they consult, and often simply make assumptions about an author's intent.

The outcome is not just terminological confusion, but also conceptual blurring. In 2016 the International Council on Systems Engineering (INCOSE) appointed a team of INCOSE Fellows to propose a definition of 'system' that would be suitable for systems engineering (SE). The team found that even amongst the relatively small number of current INCOSE Fellows there are seven different perspectives on the meaning of 'system' [8].

These conceptual differences can have profound implications. For example, in the SE field the term "emergence" is often taken to refer to system behaviours that were not designed for [9,10], while in system science it is usually taken to refer to properties the system has but the parts by themselves do not [11]. This is a significant difference because it entails that for system scientists the notion of emergence is central to the notion of what a system is, whereas for some systems engineers it is incidental.

Having multiple systems terminologies in use clearly inhibits communication between specialists even within the same community. Moreover, it is hard to build on ambiguous foundations, and we suggest that this state of affairs has impeded progress in the systems field. We have argued elsewhere [12] (p. 7) that the initial energy behind the search for a General Systems Theory (GST) was dissipated by Ludwig von Bertalanffy's inconsistency throughout his eponymous book [13], where he used the term GST in 16 different ways.

Most importantly, we suggest that this ontological confusion has constrained the uptake of systems concepts in other disciplines that might well have benefitted from them. We will elaborate on the mechanism for this last-mentioned consequence in a later section.

Our perspective in seeking a resolution to this situation is that different researchers' vocabularies are designed to capture nuances of meaning that are important in their special case contexts, and these can in principle be reconciled by seeking a more generalised concept that is consilient with each special case. An example of this in practice is the INCOSE Fellows' project mentioned above, which resulted in a definition for the word "system" that can reduce, in different situations, to the different perspectives they identified.

Drawing on a distinction from Information Science between a "domain ontology", which involves domain-specific terms, and an "upper ontology", which involves terms that are applicable across multiple domains, we argue that Systemology has the unusual potential to provide both types of concepts. In fact, we suggest that it is the failure to distinguish between the different types of terminologies applicable in Systemology that has in large part led to the terminological confusions mentioned above.

Although the unique nature of Systemology has exacerbated the challenges involved in developing its terminology, it also provides the means to resolve them. In this paper we show how systems thinking can itself be applied to the process of ontology development, usefully extending the extensive formal methods that are already in existence. Amongst the examples we develop is a proposed structure for a concept map for Systemology, developing the General Inquiry Framework structure we introduced in a companion paper in this journal issue [14].

The purpose of the present paper is to lay the basic groundwork for a community effort to develop an 'Ontology of Systemology', by:

- providing arguments for the need for such an ontology;
- disambiguating different concepts relating to termbases, vocabularies, and ontologies;
- providing background on how such ontologies are constructed;
- making suggestions for how systems thinking can aid the building of ontologies; and
- proposing a systemic and systematic framework for selecting and organising the terminology of Systemology.

We hold that the application of systems thinking to the building of ontologies would be valuable in all attempts to build ontologies, especially in areas of study with many ambiguous terms (e.g., consciousness studies) or high uncertainty about which terms are relevant for the study area (e.g., frontier science). Moreover, we believe that the structure we will propose for organising the Ontology of Systemology will aid the application of systems concepts in doing specialised research, by linking kinds of systems concepts to general kinds of lines of inquiry.

2. General Background on Ontologies and Concept Maps

2.1. Scientific and Philosophical Uses of the Term Ontology

The term 'ontology' has different meanings to philosophers and scientists. The scientific meaning derives from Information Science, where 'ontology' refers to a shared conceptualisation of a domain, presented as an organised technical vocabulary for that domain [15]. The term 'ontology' is here meant to evoke the idea that the terms and their associated concepts are the building blocks of theories in the discipline or domain, and hence reflect the most basic units of thought about the subjects under study [16] (p. 9). This is different from, but not unrelated to, the use of this term in Philosophy. In Philosophy, the term 'Ontology' refers to a discipline investigating what exists most fundamentally in the real world [17,18], and hence reflects the most fundamental units of thought for theorising about the nature of reality. In this paper we primarily intend the meaning from Information Science, although there are a few places where we will need to draw on the philosophical concept. We have tried to make the usage clear in each case.

The above scientific definition embeds nuanced meaning for the phrase "an organised technical vocabulary". In the following sections we introduce key concepts in ontology development that elaborate on this definition as a foundation for the arguments we will develop later.

2.2. Definition of a Category in Ontology

The semiotic triangle, also known as the triangle of meaning, is a simple model about the meaning of words, specifically the words that point to or reference something [19,20].

A basic analysis, which we find already in Aristotle, shows that we use certain words (called "terms") to point to or refer to 'things' that exist 'in the world' e.g., flowers, buildings, persons, love, values, numbers, emotions, ideas, beliefs and myths. We think these things exist because we have concepts in our minds that represent them to us, and experiences that we can interpret using these concepts.[1] In this way, we find our perceptions meaningful insofar as they can be associated with concepts. We can model this in terms of the semiotic triangle, as illustrated in Figure 1.

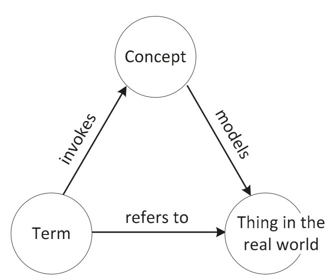

Figure 1. The semiotic triangle.

[1] For present purposes we can ignore the questions and theories about how kinds of concepts arise and come to be associated with kinds of experiences.

Note that according to this model each term has a 'referent', namely the 'thing' (phenomenon) in the real world it points to, and a 'meaning', which is the idea (concept) it evokes in our or other minds when we use the term. The concept is the mental model one has of the thing or phenomenon being referred to by the term, and hence the concept is the meaning the perceived phenomenon has for the observer.[2] The concepts we have about things in the real world are 'categories of thought', i.e., ideas that help us to understand our perceptions and hence make judgements or take action as we go about our lives. When we consciously associate these concepts with terms, we establish the elements of a language.

There is, however, a variety differential between ordinary language and thought. We can see from this simple model how miscommunication arises in common discourse, because although in discussions our use of the same term may actually refer to the same thing in the real world, the conceptual models they invoke in each of us may be different, and so we may misunderstand each other even when we correctly use the same terms to refer to the same actual things in the real world. The polysemy of terms is a problem in addition to the one of having terms that point to different referents in different contexts. This is a frequent occurrence in the common use of natural language terms. For the 500 most common words in the English language the Oxford English Dictionary records 14,070 distinct meanings—an average of 28 meanings for each word [22]. We clearly have many more concepts than we have terms, and this is why we have to create 'technical terminologies' or 'protected vocabularies' or 'technical vocabularies' for specific disciplines or areas of investigation, so that terms we use have commonly agreed unique meanings in those contexts.[3] Without such a communal consent about the use of terms, we could not hope to effectively collaborate within or across disciplines. We would be unable to agree on what we are about to do, explain why it is important, teach what we have learnt, or think in a consistent way about our subject matter. To create such a context-specific vocabulary we place constraints on meanings through definitions, the definitions specifying what attributes of the thing in question are to be included or excluded from the concept entailed by the term. This is illustrated in Figure 2.

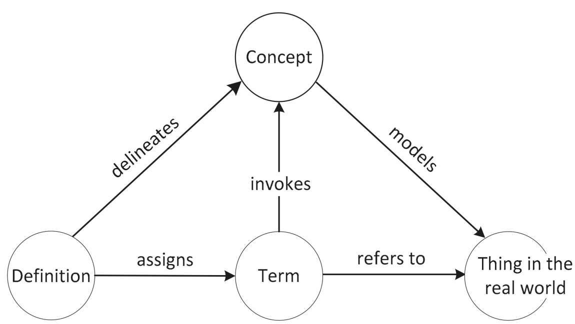

Figure 2. A category of analysis in relation to a thing in the real world.

Note that definitions can come in multiple forms [24], some of which are stronger than others, e.g.,:

- intensional definitions, which specify the meaning of a term by giving the necessary and sufficient conditions for when the term applies;

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2 We know that as a general rule we do not perceive things as they are, but 'see' them in a way that is conditioned (inter alia) by the concepts (mental models) we have of those things. This is what R.N. Hanson meant when he famously described observations as 'theory laden' [21].

3 Thomas Kuhn referred to this situation saying that for a scientific community to be in a period of normal science they must share notions, points of view, similar terminology (language use) and research scope [23].

- extensional definitions, which define applicability by listing everything that falls under that definition;
- operational definitions, which define applicable ranges of measurable parameters within which the term applies;
- ostensive definitions, which suggests where the term applies by giving indicative examples (without being exhaustive); and
- negative definitions, which articulates applicability by specifying what is excluded from the meaning of the term.

By using a careful definition, a concept can be made more precise, and the distinctions that can be made in discussing the subject can be made finer, thus improving the rigour and the expressive power of the associated term.

When we consciously restrict the meaning of a concept evoked by a term, by associating it with a definition, then we create a 'category of analysis'. In ontology development, this is referred to as a 'category'.

2.3. Definitions of a Vocabulary and a Termbase

Ontology construction typically starts with collecting terms and assigning their definitions, and such a collection is called the domain's (technical) 'vocabulary'. Such a vocabulary differs from a dictionary in that every term has a unique meaning. If the vocabulary is captured in a database, then the database is called a 'termbase', and the process of collecting, defining, translating, and storing those terms is known as 'terminology management'.

2.4. Definition of a Concept Map

Concepts are not formed or used in isolation, and it is a common practice to visualise the relationships among them using a graphical representation. Such a graphical representation is called a 'concept map'. A concept map is typically presented as a network, with the concepts placed at the nodes and the relationships as connecting lines, which can be labelled to indicate the relationship. Figures 1 and 2 are diagrams of this sort. One can make this as simple or as complex as needed for the study in hand. There are many kinds of relationships that can exist between concepts. Three common ones are the superordinate/subordinate relationship, where the characteristics of the more general concept are inherited by the more specialised ones (as shown in the "inheritance hierarchy" given in Figure 3), the whole/part relationship where the characteristics are not inherited (as shown in the "partitive hierarchy" given in Figure 4), and the associative relationship (as used in the "relationships network" given in Figure 2) (refs). Note the use of graphical conventions such as tree forms, fan forms and labelled arrows to indicate kinds of relationships. Such conventions are important but they are not standardised—for example, we could equally denote a partitive hierarchy using a tree with rounded corners to distinguish it from the square-cornered tree used to denote an inheritance hierarchy. Such a convention for a partitive hierarchy is shown in Figure 5. The kinds of relationships can of course be used in combination in the same concept map, so long as the conventions used are made clear. An example of such a mixed-model concept map is shown in Figure 6.

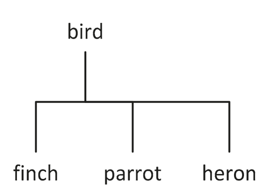

Figure 3. An inheritance hierarchy.

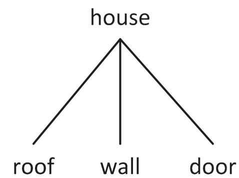

Figure 4. A partitive hierarchy.

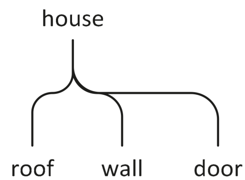

Figure 5. An alternative convention for showing a partitive hierarchy.

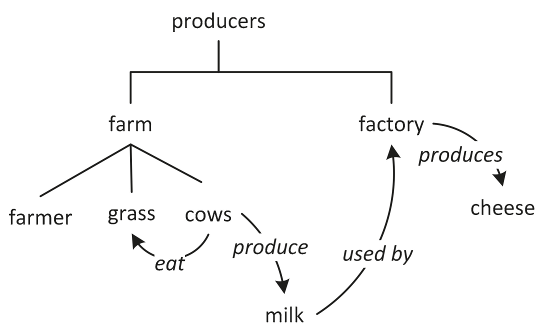

Figure 6. A concept map with multiple kinds of relationships.

2.5. Definition of an Ontology

An ontology consists of categories, as defined above, arranged according to some subject matter classification scheme, such as a taxonomy or typology [25]. The classification scheme provides a structure into which the concepts in the vocabulary can be sorted, and establishes the relationships between the concepts.

Ontologies are often specified in a formal way so they can be made machine-readable, and thus be used in application areas involving the processing of information by computers, for example in AI, machine translation, and knowledge management. However, as shown above, ontologies can be represented in a graphical way, via a concept map. Because of their visual character, concept maps are useful tools for making a concise representation of all or some part of an ontology, and thus are often used to guide the early stages of ontology development. However, formal ontologies enable the representation of vast ontologies, which concept maps cannot so easily or usefully do.

2.6. Types of Ontologies

In addition to domain ontologies, there are also 'upper ontologies' (also called 'foundational ontologies' or 'top ontologies'), which contain general categories that are applicable across multiple domains. Upper ontologies serve to provide semantic interoperability of ontologies across multiple domains. Upper ontologies provide general concepts which are common to all domains, and therefore they can provide a common foundation for domain ontologies.

Multiple upper ontologies have been developed, reflecting difference in interests or worldviews (for example, differing in how they envision the nature of time, e.g., as consisting of points or intervals). An upper ontology is developed with contributions from various philosophical disciplines. For example, one part of an upper ontology might be derived from the branches of philosophy called 'Ontology' and 'Metaphysics', providing general categories denoted by terms such as object, process, property, relation, space, time, role, function, individual, etc. [17]. Another part might be derived from the philosophy of science, providing categories denoted by terms such as energy, force, entropy, quantum, momentum, mechanism, interaction, species, etc. [26]. Another part might be derived from the philosophy of worldviews, providing general categories denoted by terms such as meaning, value, purpose, agency, freedom, knowledge, belief, etc. [14]. We can now see that another part might be derived from the philosophy of systemology, providing general categories denoted by terms such as system, hierarchy, emergence, wholeness, holon, complexity, integration, feedback, meta-stability, design pattern, etc.

The historical inconsistency and ambiguity of systemology's terms have impeded the construction of an 'ontology of systemology', and this has limited the impact of systemology in the building of upper ontologies. This is what we meant earlier when we claimed that having multiple systems terminologies limits the ability to transfer insights from systemology to other disciplines that might be able to employ them, and thus opportunities are lost for accelerating progress and avoiding duplication of effort in the specialised disciplines.

2.7. State of the Art in Ontology Development

There are several important standards that have been established for ontology development, several significant implementations of these standards, and several examples of uses of these implementations relevant to the systems community. We will not review these here, but in this section we mention some of the key ones in order to give a sense of the 'the state of the art' of the foundations and the technical maturity of the field of ontology development.

The following are the most relevant standards for terminology management.

- ISO 704:2000 Terminology work—Principles and methods
- ISO 860:1996 Terminology work—Harmonisation of concepts and terms
- ISO 1087-1:2000 Terminology work—Vocabulary-Part 1: Theory and application
- ISO 1087-2:2000 Terminology work—Vocabulary-Part 2: Computer applications
- ISO 10241:1992 Preparation and layout of international terminology standards
- NISO Z39.19-200x Guidelines for the Construction, Format, and Management of Monolingual Controlled Vocabularies

Several upper ontologies have been constructed to potentially serve as foundations for building domain ontologies (in ontology development these are called 'implementations' of the standards mentioned above). Significant implementations include:

- BFO (Basic Formal Ontology) [27]
- DOLCE (Descriptive Ontology for Linguistic and Cognitive Engineering) [28,29]
- GFO (General Formal Ontology) [30]
- SUMO (The Suggested Upper Merged Ontology) [31]
- KR Ontology [32]
- YAMATO (Yet Another More Advanced Top-level Ontology) [33]
- UFO (Unified Foundational Ontology) [34]
- PROTON (PROTo ONtology) [35]
- Cyc [36]

Some of these implementations are extensive. For example, SUMO, which is owned by the IEEE, underpins the largest formal public ontology in existence today [31]. It consists of SUMO itself (the upper ontology), a mid-level ontology called MILO (for MId-Level Ontology), and more than 30 domain ontologies (e.g., Communications, Countries, Distributed computing and User interfaces, Economy, Finance, Automobiles and Engineering components, Food, Sport, Geography, Government and Justice, People and their Emotions, Viruses, and Weather. The SUMO-based ontology cluster contains ~25,000 terms and ~80,000 relationship axioms. This ontology is free to use, unlike Cyc, for example, which is licenced.

Different implementations make different assumptions about what should be included and how it should be represented, and these choices bestow different strengths and weaknesses on the corresponding ontology implementations. A comparison of different upper ontology implementations can be found here [37], and illustrative examples of some of these implementations together with a discussion of differences in their commitments, and their pros and cons, can be found here: https://cw.fel.cvut.cz/wiki/_media/courses/osw/lecture-08matching-h.pdf.

Ontology standards and formal implementations have thus far had little recognition or impact in the systems community. For example, INCOSE's Systems Science Working Group (SSWG) initiated a project in early 2011 to develop a unified ontology around the concept of 'system', but effectively abandoned the project after 2.5 years, concluding that "the attempt to converge on unified concept maps let alone any conversion of these to ontologies may be futile".[4] The working group did consult ISO standards about specific terms (e.g., 'context' and 'environment'[5]) but not any of the ISO standards about ontology development. They did reflect on the KR ontology, but there is little trace of it in the concepts maps the working group produced.[6]

A significant, but limited, attempt to apply formal ontologies occurred in 2018, as part of the abovementioned INCOSE Fellows Project on the definition of 'system'. This project demonstrated how their proposed definition of 'system' might be represented using BFO [41].

Although we have well-developed standards for the procedure of building up a concept map for a domain of interest (for a general overview, see [42]), the task can be intellectually challenging. We will discuss some of these challenges in the next section.

3. Systems Thinking as an Aid to Ontology Development

3.1. General Challenges in Ontology Development

As mentioned above, there are well-established methods and frameworks for constructing ontologies. Nevertheless, constructing a domain ontology can be extremely challenging as an intellectual exercise. The basic challenges are to:

- Keep the definitions clear while expressing them as compactly as possible;
- Limit the conceptual scope of a term to the minimum without trivialising it;
- Minimise the number of terms employed without leaving out important distinctions;
- Maintain coherence of the network of terms and definitions;
- Maximise the use of categories and relationships already established in a relevant upper ontology, to avoid duplication of effort and to maximise interoperability with other domain ontologies; and
- Maximise compatibility between proposed terms, definitions and meanings already present in the scholarly literature.

We shall refer to the items in the above list, taken as goals for ontology development, as 'general principles in ontology development'.

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4 The working group's final report is available here: [38]
5 See pages 4-5 of the progress report available here: [39]
6 See, for example, page 6 of the report available here: [40]

It is unlikely that all of these criteria can be satisfied simultaneously, so some compromises will have to be reached. It is therefore important to bear in mind the impact of changes at every step, not only on the new additions themselves but also on the whole ontology developed thus far.

3.2. The Nature of Systems, and the Systemicity of Ontologies

We mentioned earlier the interdependencies between the concepts in an ontology, without exploring an important implication of these relationships, namely that an ontology is a *system* in a sense that is much deeper and richer than the fact that it instantiates a taxonomic system.

According to one systems definition, due to Anatol Rapoport and popular in the systems science community, a system is a whole that functions as a whole because of the interactions between its parts [43]. This is consistent with the definition of systems now emerging in the systems engineering community, according to which "A physical system is a structured set of parts or elements, which together exhibit behaviour that the individual parts do not" and "A conceptual system is a structured set of parts or elements, which together exhibit meaning that the individual parts do not" [8,44].

In the sense of these definitions, an ontology is a conceptual system. A ontology's systemicity is evident in the way that the scope of the definitions of existing terms within an ontology are constantly adjusted to accommodate new terms and their definitions in a way that maintains the distinctness of each term's meaning, the overall coherence of the relationships between the terms, and changes in the relationships between the domain of interest and other domains.

In our view, recognising that an ontology is a system is important because it implies that we can leverage knowledge that we have about systems in general, to help us meet the specific challenges outlined above. In the subsections to follow, we will demonstrate various ways in which systems concepts and principles either enrich our understanding of existing practices in ontology development or suggest helpful new approaches to it.

3.3. Systems Thinking for Ontology Development

To leverage our knowledge of systems in the context of ontology development, we have to employ what is known as "Systems Thinking". There is no general agreement on what 'Systems Thinking' is, but there have been many attempts to define some 'common core' for it, e.g., [45,46]. A challenge to such assessment and interpolation is that the body of literature on this subject is extensive, and consequently it is easy for any particular review to overlook important works.

We regard the framework developed initially by Derek Cabrera as the most representative account of what Systems Thinking is, because he used formal scientific methods to distill and evaluate the concepts and themes relevant to systems thinking. Cornell University awarded a PhD for this work in 2006 [47]. It has since been extensively discussed in the academic literature (e.g., [48]) and was recently published as a popular book co-authored with translational scientist Laura Cabrera [49].

We took Cabrera's definition of 'Systems Thinking' as our standard for the present study [47] (p. 176):

"Systems thinking is a conceptual framework, derived from patterns in systems science concepts, theories and methods, in which a concept about a phenomenon evolves by recursively applying rules to each construct and thus changes or eliminates existing constructs or creates new ones until an internally consistent conclusion is reached. The rules are:

- **Distinction making**: differentiating between a concept's identity (what it is) and the other (what it is not), between what is internal and what is external to the boundaries of the concept or system of concepts;
- **Interrelating**: inter linking one concept to another by identifying reciprocal (i.e., 2×2) causes and effects;
- **Organising Systems**: lumping or splitting concepts into larger wholes or smaller parts; and

- **Perspective taking**: reorienting a system of concepts by determining the focal point from which observation occurs by attributing to a point in the system a view of the other objects in the system (e.g., a *point of view*)".

Cabrera called this the 'DSRP' framework, after Distinction-making (D), Organising Systems (S), Inter-relating (R), and Perspective-taking (P), and from this he developed an application method based on what he now calls 'the Distinction Rule', 'the Relationships Rule', 'the Systems Rule', and 'the Perspectives Rule' [49] (p. 9). Each rule is defined in terms of a concept and its dual, namely thing/idea and other (D), cause and effect (R), whole and part (S), and point/subject and viewpoint/object (P) [47] (p. 178), [49] (p. 9).

In what follows, we will introduce various concepts that are important in systems science and show how these concepts and Systems Thinking (in the mold of DSRP) can support efforts in ontology development.

3.4. Systems Principles in Ontology Development

3.4.1. Dialectical Feedback

As mentioned above, a key challenge for ontology development is to ensure that concepts are clear and their definitions are succinct without sacrificing their utility: after all, a "good" concept represents the smallest unit of knowledge carrying as much meaning as possible [16] (p. 9). One way to achieve concise definitions is to leverage a systems principle that originated in dialectics. Dialectics was an ancient debating technique, dating back to Plato, where persons with opposite points of view tried to find out the truth about some matter through reasoned means by analysing the implications of their opposing views. Dialectical reasoning found a modern incarnation in Hegel, whose dialectical method explicitly sought insight by exploring the tension between opposing concepts (rather than persons with opposing views). Hegelian dialectics has found a more modern home in systems theory, in the sense that the systems perspective looks for understanding by considering not only the nature of the parts (the reductionist perspective) but also in the relationship to the context/environment, and hence aims to explain a phenomenon not only in terms of its composition but also in terms of its relationship to what it is not, that is, to what is different from it or contrastive to it [50,51].[7] In this way, the meaning of the initial 'concept of interest' is deepened and clarified by making it contingent on also understanding the concept associated with its opposite and the nature of the relationship between the two. This suggests that looking for dialectical opposites might be a useful strategy for clarifying and compacting definitions for terms in an ontology, because it is often easier to say what something is not than to say what it is. Note that this is not merely a matter of making a negative definition of the 'concept of interest', but rather to define it and its contrary jointly, making the relationship between them part of how either concept is understood.[8] In practice, this technique would typically be applied where the initial concept is difficult to define precisely, or where there is controversy about how the representing term should be used.

For example, imagine we need to define a term such us 'healthy' in the context of human persons. To define a basis on which we might, in general, regard a person as healthy is a challenge because human beings are complex systems with multiple properties and state variables, and there may be a large number of ways in which these can be balanced so as to add up to an assessment of 'heathy'. How can we know that our definition is adequate and comprehensive? The systems principle of dialectical feedback suggests that we start by looking at its opposite, 'unhealthy'. We can easily conceptualize this, because an unhealthy person could be defined as a person presenting any of the

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[7] This idea is explicitly captured in 'Distinctions Rule' of the DSRP framework, but the other DSRP rules also employ interrelated dichotomies in line with the notion of dialectical feedback.

[8] This also corresponds to the 'Distinction' rule of Cabrera et. al.'s 'DSRP' Framework [48].

signs that we know of as originating in diseases or traumas, e.g., fevers, pains, cardiac arythmias, swellings etc.[9] We could recognise such signs even in the absence of being able to diagnose the specific disease or trauma, so this definition of 'unhealthy' is not contingent on how comprehensive our knowledge of diseases and traumas are. However, the list of signs suggests a list of relevant physiological parameters that are disturbed by diseases and traumas. We can in principle determine the normal ranges of those parameters in persons not suffering from a disease or trauma, and thus we can now define a healthy person as someone exhibiting physiological signs that are within normal ranges, as shown in Figure 7. This is a simplified example but it demonstrates how we can quickly get to a satisfactory definition by working with the relationship between contraries. Note that the two definitions are linked by the concept of 'signs', which we had to define along the way, and also a special notion of 'normal', which was introduced to express the nature of the contrast between the two definitions. The dialectical tension is not captured by the fact that both definitions involve the notion of 'signs', but by the two definitions being grounded in the signs having different ranges for their parametric values. It is quite common when refining terms in this way to have to also define or refine other terms and articulate their relationship to the categories we are working on. This is a positive phenomenon in ontology development because it improves the terminology in a broader sense than we set out to do, and this may make it easier to refine other terms later on.

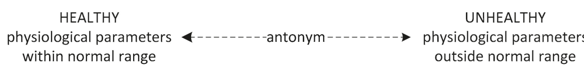

Figure 7. A concept map for the categories 'healthy' and 'unhealthy'.

The mapping convention used here is to display the categories in upper case, terse definitions below them in lower case, and the relationships using graphical elements, in this case a dashed arrow to indicate the 'antonym' relationship.

We will now illustrate this use of the dialectical feedback principle in a more complicated case involving a category for an upper ontology. Imagine we want to create a top category for an upper ontology. This would be the most general category in our ontology, so that every other category will be a specialised instance of it. The term must be able to refer to anything of any nature whatsoever, that is, irrespective of whether the referent is real, imaginary, abstract, ideal, etc. We need to select a term that could usefully stand for that meaning and determine a nontrivial definition. It would be trivial to define it as "the designator for anything that exists" because then it (a) begs the question of what we mean by 'exists', thus subverting our quest for creating a top category, and (b) it gives us no guidance for then creating subcategories (e.g., via inheritance relationships).

To start, consider terms that might do, for example: thing, object, entity, existent, particular, universal type or individual. All of these have been used as top categories, e.g., BFO, SUMO, and DOLCE use 'entity', Cyc uses 'thing', KR Ontology uses a symbol, T, defined as 'universal type'. In the branch of philosophy called 'Ontology', common choices are 'object' and 'particular' (e.g., [17,52]). Given this variety, it will be hard to achieve one of the goals listed in Section 3.1., namely to "maximise the use of categories and relationships already established in a relevant upper ontology". However, we can reason about our choice in terms of another mentioned challenge, namely to "maximise compatibility between proposed terms and meanings already present in the literature". None of the available terms seems ideal, e.g.,:

- 'thing' seems inappropriate for a category that might have 'values' or 'ideas' or 'processes' as subcategories;

9 In medical practice, a sign is something objectively observable, as opposed to an indication via a subjective report. Vomiting is a sign, nausea is not. Signs reflect measurable physiological parameters, whereas subjective reports reflect psychological impressions that may or may not have a basis in physiology.

- 'object' seems inappropriate for a category that might have 'force fields' or 'consciousness' as subcategories;
- 'entity' sounds like a term more appropriate to referring to some kind of living being;
- 'individual' sounds like a term more appropriate to referring to persons;
- 'particular' could suggest an interpretation in the sense of 'not general', whereas generality is exactly what is being aimed for;
- 'existent' is naturally an adjective and seems clunky when used as a noun; and
- 'T' is not a term but a symbol.

The least potentially confusing option seems to be 'existent', and therefore we recommend its selection while acknowledging that other choices also have merit.

Moving on to defining it, consider the dialectical opposites of the candidate terms. For most of them the obvious choice for an opposite does not work, as they invoke inappropriate opposites. Consider the pairings thing/nothing, object/subject, entity/non-entity, existent/non-existent, particular/universal, individual/group, and T/⊥ (universal type/paradoxical type in KR Ontology).

Only the antonyms 'non-existent' and 'nothing' are relevant concepts as antonyms of the top category ('existent').

A common definition of 'non-existent' is: "does not exist or is not present in a particular place"[10]. This is not helpful, because it involves either a simple negative definition (which is trivial) or one that is misleading from the dialectical feedback perspective, because 'not present' would suggest an 'existent' has to be somewhere; but this is an unwarranted constraint, because some kinds of existents are not inherently located 'somewhere', e.g., numbers or geometrical shapes.[11]

The antonym 'nothing' is helpful, however, because it suggests that 'nothing' is a special kind of *thing*, namely a 'no-thing'. This is perhaps just a quirk of language, but it puts us on the right mental track, because we can now say that a no-thing is something that has no properties.[12] If it had any, those properties would indicate what sort of thing it is, in which case it would not be a no-thing. This suggests the idea that to be an existent is to have properties. Properties cannot be free-floating but have to belong to some existent (there are no actual Cheshire cat smiles without Cheshire cats). So this gives us a concise and useful definition: an 'existent' is 'a bearer of properties', and 'nothing' is 'not a bearer of properties'. Note the role of properties as a link between these categories, analogously to the role of 'physiological parameter' in the previous example about health.

This work enables us now to draw the diagram given in Figure 8. It is simple, but its utility will be demonstrated in the next section.

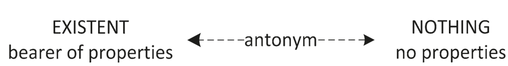

Figure 8. A concept map for the categories 'existent' and 'nothing'.

3.4.2. Emergence, Wholeness and Coherence

Systems are wholes, that is to say they have properties (called 'emergent properties') that only exist at the level of 'the whole', and are not present in the parts or the relationships among the parts [8] and [11] (p. 12), [53] (p. 55). For systems to function as wholes, their parts must work together in a coherent way, otherwise instabilities would arise to undermine the integrity of the system and its 'wholeness' would break down (the emergent properties would degrade or be lost). This idea is important when thinking

[10] See, https://dictionary.cambridge.org/dictionary/english/non-existent

[11] Numbers and shapes are abstract existents, and exist (somehow) independently of our knowledge of them—any sufficiently advanced civilization can independently discover them.

[12] In Ontology (the branch of philosophy) a 'property' as defined as a way some existent is (e.g., green, or smiling, or charged) [17]. No existent, no properties thereof . . .

about ontologies. In a dictionary, terms have multiple meanings, and the applicable meaning is determined by the context in which the term is used. In an ontology, terms must always have unique meanings. This can ostensibly be achieved via a list of terms each with an associated single definition, but in practice this can be confounded by the fact that a term definition may well use other terms. This opens up the possibility of definitions being ambiguous, circular, or incoherent because of the connected meanings of those other terms. The risk of this occurring can be managed by creating a network of categories in which the relationships and interdependencies between the categories are made explicit, easy to trace, and open to assessment. This makes it possible to check that definitions are not circular, that concepts do not have unwarranted overlapping meanings, and that the definitions express all the nuances we need to cover in order to discuss the subject of interest.

The network of terms thus forms a coherent system, in which the mutual coherence of the definitions makes the system stable as a whole, and the distinctness of individual categories makes the categories powerful tools for analysis, enabling lucid thinking, theorising, and discussion in the disciplinary context. The net effect is an ontology that *as a system* has the (emergent) stability and coherence needed to ensure and sustain the stability and coherence of the discipline of which it is the conceptualisation.

Maintenance of the ontology *as a system* is thus of ongoing importance. As a discipline grows in conceptual richness, we cannot merely add terms and new definitions but must continuously review the relationships between the employed categories to ensure we maintain the coherence of the systemic ontology.

A well-known example of an ontological system that derives its utility from the clarity and distinctiveness of its categories, and its overall coherence as a system is the Linnaean system for classifying organisms. A simplified representation of a fragment of it is given in Figure 9. This is an inheritance hierarchy. The relationships are not labelled because they are all of the same kind, in this case the 'is a' relationship (reading upwards), e.g., a reptile is vertebrate, a vertebrate is an animal.

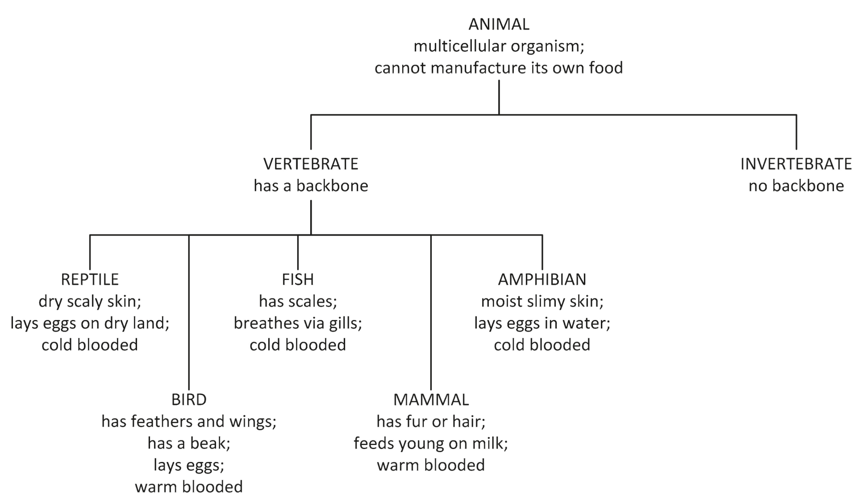

Figure 9. A concept map of a part of the Linnaean classification system.

Although the illustration in Figure 9 is very incomplete, it serves to show how a concise concept map can help to identify the concepts that recur across definitions and check for ambiguity and circularity. It also simplifies the communication of a definition, given that inherited aspects do not need to be repeated, so the distinctive defining characteristics are clearly highlighted at each level.

We will now demonstrate the application of these systems principles in a more complicated example, expanding the upper ontology model we worked on in Section 3.4.1. We have a 'most general' category, 'existent', in hand, so let us now consider what might appear on the next level(s) of our upper ontology and sort them into a systematic and coherent arrangement. First, let us assemble a list of candidate general categories as might be denoted by terms such as thing, process, event, relationship, and concept. For this demonstration, we will set aside whether that selection is an exhaustive set or not, and we'll gloss some of the deep debates in philosophy about the nature of fundamental quantities such as space and time.

To get started in thinking about these categories, we need to establish some additional concepts, for which we can find examples in the existing philosophical literature and formal ontology frameworks. For now we will list them as assumptions or conventions for this demonstration, as follows:

- We will use the term 'substance' to refer to 'stuff something might be comprised of', so if something is made of stuff we will refer to it as 'substantial, and if not then as 'insubstantial'. The difference between them is that substances are part of the real world and have inherent causal powers;
- We will regard time as a kind of metric and not as kind of thing or substance, enabling us to specify, in relation to the temporal metric, such notions as 'before', 'during', 'interval', and 'after';
- We will regard space as having metrical properties, enabling us to specify, in relation to the spatial metric, such notions as size, shape, 'next to', 'to the left of', and 'above'; and also as being substantial. This is consistent with the idea in contemporary physics that 'empty space' is not really empty but is a substance comprised of virtual particles, thus constituting what is called the quantum vacuum;
- If all the aspects of an existent exist at the same time, we will call it an 'occurant' (e.g., this apple), and if the aspects of an existent are spread out over an interval we will call it a 'continuant' (e.g., this football match). We will disambiguate 'continuant' from the case where an occurant persists in time by describing such an occurant as being *also* an 'endurant'. An occurant that does not endure is an instantaneous one;
- We will take it for granted that for a substance to exist it must be located in time and space; and
- We will take 'state' to stand for the instantaneous values of an existent's properties at a moment.

Now we can construct initial minimal definitions for our basic categories, inter alia using the general and systems principles already discussed. First, we might assign attributes to our categories as follows:

- Thing: spatial & temporal properties, substantial, occurant (things could be either enduring or instantaneous);
- Process: spatial & temporal properties, substantial, continuant;
- Event: spatial & temporal properties, substantial, instantaneous;
- Relationship: spatial and/or temporal properties, insubstantial, occurant, or continuant; and
- Concept: no spatial properties, logical properties, insubstantial, occurant.

With these characterisations in mind, we can now propose definitions that encapsulate the relationships between the categories, for example:

- Thing: a substantial occurant;
- Concept: an insubstantial occurant;
- Event: a change in the state of an existent;
- Process: a series of events; and
- Relationship: a conceptual association between things, processes, events, or concepts.

Note that this list has been arranged so that we define the categories in a sequential way, so that no definition employs categories that have not yet been defined. This not only helps us to check for collective coherence but it also entails that some categories are more fundamental than others. We can now illustrate this in a concept map as shown in Figure 10.

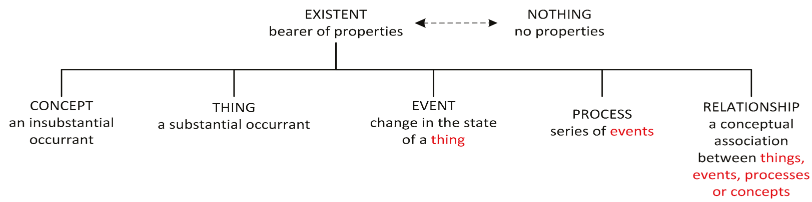

Figure 10. A partial concept map of upper kinds of existents.

In Figure 10 we have an inheritance hierarchy, except from the antonym relationship indicated by the dashed arrow. The categories have been arranged so the more fundamental ones are above or to the left of more derivative ones. This systematic buildup of meanings is indicated by the colored terms.[13] An implication of these systematic relationships is that, in a domain in which these definitions are used, the foundational existents are things and concepts, not processes or events, and this will be reflected in research planning and theory building. This prioritisation however reflects only one possible metaphysical stance, and there are other perspectives in which processes or events, or even other categories such as percepts or measurements or information, are considered fundamental. This debate is inconsequential for the purposes of the present demonstration of how general systems principles can, in principle, aid in the development of an upper ontology.

Having demonstrated this method, it is now possible to apply it to a more extensive effort involving further foundational categories, such as space, time, law, truth, cause, real, abstract, imaginary, naturalistic, etc. These terms are ubiquitous in general texts in Ontology and Metaphysics, which can be consulted for identifying both category instances and the controversies over their definitions. A useful text is the two volumes on ontology by Mario Bunge [54,55], and recent works on the metaphysics of scientific realism, e.g., [56,57]. Other useful references include [26,58–61].

That said, the method discussed here is not specifically aimed at developing upper ontologies but may be useful in distilling any specialised vocabulary into an ontology.

3.4.3. Boundaries, Contexts and Levels

The notion of 'boundary' is central to both systems science and systems thinking, and because ontologies are (conceptual) systems, we can gain helpful insights for ontology development by considering an ontology's boundary from a systems perspective. As we will show, proper attention to the ontology's boundary can facilitate leveraging existing work in a thoughtful and managed way, thus increasing a project's power while constraining its scope and making it more efficient, and consequently resulting in an ontology with a broader impact potential.

The 'boundary' concept is a nuanced one in systemology. Key defining characteristics of a 'boundary' have to do with where the boundary is drawn, which can be objective or subjective, and how permeable it is to flows of influence. We will discuss these aspects more deeply first, pointing out how each aspect relates to an ontology's boundary, before bringing the ideas together to apply to both the system of interest and the conceptual system that is the ontology, which may well have different boundaries.

First, consider systems with inherent boundaries for which there can be objective criteria. There are two ways such boundaries can be recognised, that draw on the mechanisms by which they are established. Systems are called 'wholes' because they exhibit properties the parts do not have by themselves [11] (p. 17), and the system boundary is defined by the limits of the region over which

[13] As we developed this framework no additional concepts surfaced that had to be included in other to complete the framework. This is unusual in such work but it does suggest that the terms we picked out form a natural grouping, and might thus be stable when we start to expand the framework to consider further fundamental categories.

these emergent properties are present [11] (p. 36), [62]. In an ontology system, a key emergent property is its coherent meaning, as discussed before. Another recognisable sign derives from the fact that a system's parts interact or interrelate in such a manner as *to establish and maintain* a boundary that demarcates the identifying characteristics of the system, via which it can be distinguished from its environment or context [62,63]. These interactions and relationships between parts produce a region of high organisation compared to their immediate environment, so that we could characterise systems as persistent regions of low entropy in a generally dissipative environment [63] (p. 3). This enables us to recognise a system boundary by the gradient between regions of low entropy and relatively higher entropy. In an ontology this might manifest in the connectedness and mutual coherence of concepts.

Where the boundary of a system is not clear, researchers can determine them intuitively to encompass what they judge to be the limits of the system of interest. This is a common phenomenon in systems practice, where it often difficult to identify all the stakeholders in a systemic intervention. It is also common in frontier research, where it may be radically unclear what factors contribute to the phenomenon under investigation. In this case, a subjective assumption followed by monitoring and adjustment is appropriate.

Turning secondly to the question of permeability, the boundaries of all known systems, apart from the universe, are 'open', that is to say, it is possible for matter, energy, and/or information to flow across the boundary. The internal systemic interactions modulate these transfers, so that the system can change without undermining its identity. The system thus changes in a way that pursues some kind of balance between the state and properties of the system and the state and properties of its environment. As a consequence, both the position of the boundary and the emergent properties of the system can change over time. Open boundaries thus create the possibility for systems to evolve or adapt (or be adapted via interactions coming from the environment). For ontology development, a key point is that the boundary is managed in a controlled way from within, but it is not rigid.

Lastly, it is important to note that although the environment is distinct from the system, the environment can be systemic in its own right or contain other autonomously existing systems. To prevent confusion given these possibilities, the system that is the focus of study, design, or intervention is often called the 'system of interest'. While the system of interest is a part in a larger system, it is called a 'holon' [64], and some holons cannot exist autonomously, for example an organ in a body. In such a case, an ontology for a system of interest would be of limited use unless it was integrated with the broader ontology in a consistent way. If the environment contains autonomous systems that can interact with the system of interest to produce a higher-order system, then that collection of systems is called a 'system of systems', for example a military defense force composed of operational units that work in a centrally coordinated way but can in principle operate independently. Here, the ontology development must take account of the actual or potential interdependencies. For example, the ontology of genomics is a holon within the ontology of biology, and if a multi-disciplinary team work on the same project then their specialist ontologies form a system of systems.

We will turn now to how these ideas can collectively impact ontology development.

Any specific ontology supports a discipline that is concerned with some subject matter, and therefore the ontology is restricted to the scope of that interest. This implies a 'boundary' that demarcates between categories that are of direct interest to the specific discipline and categories that are indirectly relevant or only relevant to other disciplines. If such a spectrum of relevance can be identified, it would allow us to manage the scope of the ontology representing our area of interest, and identify other ontologies we can employ or influence without having to take responsibility for their development. This increases both the effectiveness and the efficiency of our ontology development.

There are different ways to identify the nearest or most relevant neighbours. For example, different disciplines study different kinds of systems, and these can be organised into levels according to their complexity, resulting in a subsumption hierarchy, as shown in a simplified way in Figure 11. At every level, systems can have as parts systems from the 'lower' levels, and any system can have in its environment any of the kinds of systems in the hierarchy.

socio-technical systems
social systems
biological systems
macro-physical systems
chemical systems
micro-physical systems

Figure 11. A levels hierarchy of systems ordered by complexity.

Each level can be associated with a disciplinary ontology, e.g., physics, chemistry, geology, biology, sociology (the list is not comprehensive here, but just meant to be illustrative of the principle at stake). What we can now see is that every domain ontology has boundaries that link it both to an environment comprised of other domain ontologies, as well as to the upper ontology that is general across those domains. We can illustrate this as shown in Figure 12, which is of course *not* a subsumption hierarchy. The boundaries between the ontologies are indicated with a dashed line to remind us that these are open boundaries that will in fact be located more flexibly and differently to the disciplinary ones.

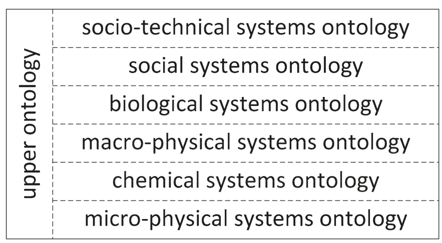

Figure 12. A systemic hierarchy of ontologies.

The implication is that to build an adequate ontology, the developer must not only take into account the upper ontology as providing relevant categories that do not have to be independently developed, but also the categories in adjoining domains, *especially those of its immediate neighbours*. What we therefore have is a kind of ontology ecosystem, in which the development of any one ontology has (ideally) to proceed in a way that preserves a coherent balance between its own categories and the categories in the ontologies reflecting its environment. If this is not done, the result is silofication of the disciplinary domain. This can inhibit progress (through lack of awareness of useful categories of analysis existing in other domains) or waste resources (through duplication of effort to create categories already existing elsewhere or pursuing blind alleys already excluded from being potentially fruitful via insights captured in alternative domain categories).

Recognising and working with boundaries in this way not only makes ontology development more effective, efficient, and impactful, but such open boundaries can also enhance the abilities of researchers who cultivate awareness of categories in related domains. An accessible example of the value of such 'multidisciplinary' competence is the case of William Harvey, who was a physician but also had a good grasp of the categories of the modern scientific method then emerging from the work of people such as his contemporary Galileo, and also the categories of mechanics. This allowed him to make systematic observations in his research and propose a mechanical analogue for the nature of heart, by characterising it a kind of a pump [65] (pp. 49–54). Such multi-disciplinarity and inter-disciplinarity is currently driving a rapid rise in technological innovation, and is being heavily promoted by funding bodies under the rubric of 'convergence' [66]. This is an important development, but much more needs to be done to break down silos between ontology development projects, because, as has been noted, silos often persist due to political or economic considerations rather than because scholars or practitioners are overly protective of their niche in the academic ecosystem, or unappreciative of the systemicity of academic knowledge [67]. While funding bodies and commercial interests are driving convergence in technological projects, ontology projects are not yet showing significant convergence [8,68], especially in the area of upper ontology development (as shown by the plethora of ontology implementations listed in Section 2.6). Lack of ontology convergence can raise risks for complex projects though lack of clear communication within a multi-disciplinary team.

An important consequence of the open-ness of the boundaries of ontologies (and their corresponding disciplines) is that the boundaries change over time as information flows across them, changing our understanding of where the boundaries should usefully lie. In this way, boundaries could be changed to include categories newly discovered or formerly viewed as not relevant, or to drop categories that have become superfluous or been taken over by other ontologies. In this sense, ontologies evolve over time, and the work of ontology development is not only never complete, but ontologists must keep tracking developments in adjacent ontologies so they can effectively and efficiently manage where the boundaries of their ontologies are.

3.4.4. Isomorphic Systems Patterns

A key concept in systems science is the idea of 'isomorphies'. They represent similar patterns of structure or behaviour that recur across differences in scale or composition, and so have significance across multiple kinds of systems. For example, spiral patterns occur in sea shells, sunflowers, peacock tails, tornados, and galaxies. Such patterns represent systemic solutions to similar optimisation problems in varied contexts [12] (pp. 109–110), and therefore can help designers to find optimal or elegant solutions to design challenges [69]. Many systemic isomorphies have been identified so far, and useful overviews and discussions of them can be found in the works of Len Troncale [70–72].

These systemic isomorphisms suggest the existence of universal principles behind the way in which enduring complex systems are ordered. This is essentially the argument for the existence of a general theory of systems [12] (pp. 108–110) and for the general systems community's belief that not only is nature a unity despite its phenomenological diversity, but also our knowledge of reality can be unified despite the many apparently intractable gaps in our current body of knowledge [12,13]. However, the most significant point about isomorphisms for present purposes is that they are routes to achieving optimality and robustness in system designs. Given that an ontology is a system, we can now look for isomorphisms that might help us design robust or elegant ontologies. Most of the isomorphisms noted to date have been discovered by studying concrete systems, but some have arisen in the study of conceptual systems and some occur in both types. For example, Zipf's Law patterns occur in both physical and conceptual systems [73].

Ontologies capture foundational information about a field of interest, and recent work in systemology has revealed the existence of a systems isomorphism related to kinds of knowledge. A paper discussing this is included in this special issue of *Systems* [14]. The isomorphism is captured in a systematic and systemic "General Inquiry Framework" that provides categories for organising knowledge in multiple specialised contexts, such as when designing a product, solving a problem, investigating a phenomenon, or documenting a worldview. The framework was generalised by abstracting from a more specialised "Worldview Inquiry Framework" used for exploring, documenting, and comparing worldviews.

In the next section, we will show how this framework can be adapted to provide a starting point for an Ontology of Systemology. For a start, consider the top-level categories of the General Inquiry Framework given in Figure 13.

Note that the term 'Ontology', here denoting the first category of knowledge, refers to Ontology in the philosophical sense, which deals with foundational categories, and is distinct from the idea of an ontology as the conceptualisation of a domain. The knowledge isomorphy suggests that any systematic pool of knowledge can be organised according to this structure, including, of course, the information in an ontology. An example of this is given in [14], where a concept map for worldview categories is given in its Figure 1. We would suggest that the General Inquiry Framework, treated as a systemic isomorphy, provides a useful tool for ontology development, particularly for developing ontologies for areas of study where there is uncertainty about what categories are needed, for example in nascent domains such as systemology, or frontier domains such as consciousness studies. The list of possible knowledge categories, as illustrated in more detail in [14], can provide useful suggestions for gaps in the knowledge base or opportunities for investigation in research. In the next section, we will illustrate the application of this isomorphy for the case of Systemology.

General Inquiry Component	Typical Information Component Questions
Ontology (of area of interest)	What are the fundamental existents or fundamental categories of thought for our area of interest? What variety of things occurs in the area of interest? What features and attributes identify them?
Metaphysics (of area of interest)	What is the nature of the entities contained in the area of interest? What are their generic powers and limitations? What powers are unique to these entities?
Cosmology I (cosmology of context of subject of interest)	What is present in the context or environment of the subject of interest? What are the capabilities of those entities? How are they organised? How did that scenario come about and how will/could it change? What are the relationships between the specific subject and its context? How do they condition each other?
Cosmology II (cosmology of subject of interest)	What specific or specialised thing is the particular subject of interest? What are its defining attributes? How did/could the subject of interest originate? How did/could it develop into its present/desired state? How might/should it change in the future, and what will/could become of it?
Axiology (of subject of interest)	What is the importance or value of the specific subject of interest's existence and behaviour? Why does it matter what it does?
Praxeology (of subject of interest)	What functions can the specific subject of interest perform? What is the meaning or purpose or relevance of its activities? By what mechanisms are these outcomes achieved?
Epistemology (of area of interest, and of the specific subject of interest and its context)	What can we know about the subject of interest and its context? What methods can reveal this information? How can we assess the comprehensiveness and credibility of this information?

Figure 13. The Top Categories of the "General Inquiry Framework" [14].

4. A Concept Map towards an Ontology of Systemology

We have in this paper argued for the need for an ontology of systemology, discussed the value of concept maps especially in the early stages of ontology development, and suggested how systems thinking can help advance the practice of ontology development. The overarching purpose of the present paper is to advocate for, and help start work towards, the development of a standardised ontology of Systemology. To show how the principles of ontology development and systems thinking as discussed in the present paper can facilitate this development, we now present in Figure 14 a first draft of a concept map representing core terms from systemology, arranged according to the categories of the General Inquiry Framework. This diagram is meant to be provisional and illustrative only, as a basis for discussion and further development.

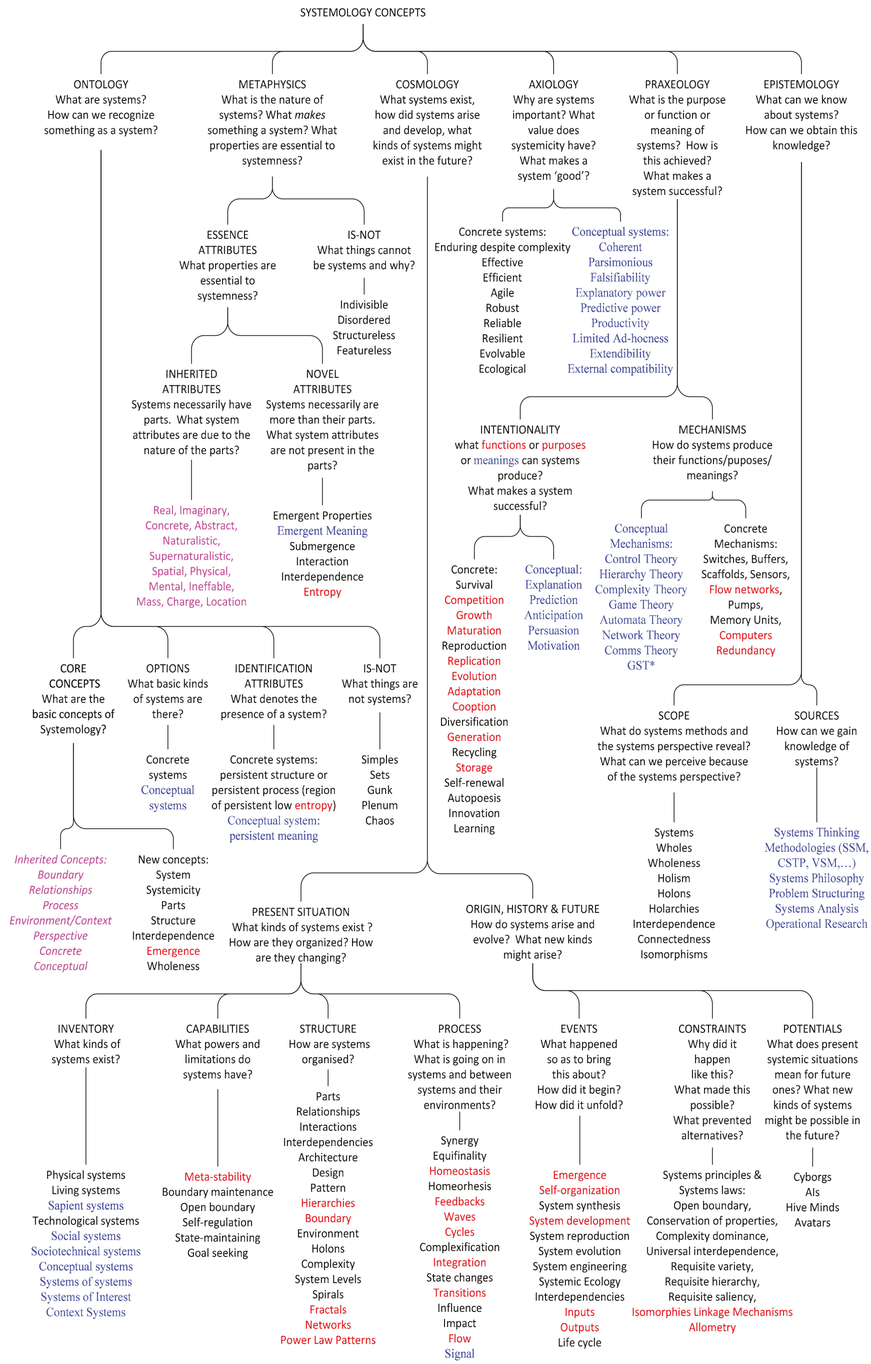

Figure 14. The Top Categories of the "General Inquiry Framework".

It is important to note that that the given concepts are not intended as answers to the questions posed under each knowledge category. The questions are there, in this context, to stimulate reflection on what concepts might be required to answer such questions. The listed concepts are then candidate concepts to be defined in the ontology for systemology, in order to facilitate proposing or developing answers to be captured in the knowledge base of systemology. The concepts listed are by no means a complete set. We have tried to show relevant concepts in each knowledge area, to show to employ this framework, but a more detailed development is needed based on the collections of definitions such as those mentioned in Section 1.

In order to facilitate discussion relative to upper ontologies, contextual domain ontologies, and other works on the categories of systemology, we have changed some of the colors and fonts in the presented concept map to illustrate some of these linkages, as follows:

- Blue serif font indicates concepts relating to conceptual systems rather than physical ones;
- Red indicates concepts occurring on the isomorphy lists of Len Troncale, to show how this presented structure can assist in their organisation; and
- Pink indicates concepts inherited from upper ontologies.

Note that 'Ontology' only appears once; there is no need to distinguish between Ontology I and Ontology II because the same concepts are needed to describe the cosmology of the system of interest and the context.

5. Conclusions

Systemology is a transdiscipline, which means that its principles and methods could in principle be useful across a wide variety of disciplines and problem contexts. However, as we have argued, these potential benefits are undermined by the lack of a consistent disciplinary terminology, which makes it hard to convey systems concepts to other disciplines. In fact, this lack can even make it hard to communicate between different systems specialisations. In this paper we have presented a conceptual framework for selecting and organising the terminology of systemology, and we call for a community effort to use this to develop an "Ontology for Systemology". We also offer the approach by which we arrived at this framework as an example of how the systems perspective can enrich other disciplines' methodologies.

Author Contributions: The project was conceived and managed by David Rousseau. David Rousseau, Julie Billingham and Javier Calvo-Amodio contributed equally to the research and the writing of the paper. David Rousseau prepared the diagrams.

Funding: Financial and material support for the project was provided by the Centre for Systems Philosophy, INCOSE and the University of Hull's Centre for Systems Studies.

Acknowledgments: We would like to thank the two anonymous reviewers of this paper for their helpful comments, which have greatly aided us in improving the structure and clarity of this paper.

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

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A Systematic Framework for Exploring Worldviews and Its Generalization as a Multi-Purpose Inquiry Framework

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Received: 31 March 2018; Accepted: 5 July 2018; Published: 10 July 2018

Abstract: Systems science methodologies do not have a consistent way of working with worldviews, even though determining stakeholder perspectives is central to systems thinking. In this paper, we propose a comprehensive "Worldview Inquiry Framework" that can be used across methodologies to govern the process of eliciting, documenting, and comparing the worldviews of stakeholders. We discuss the systemicity of worldviews and explain how this can help practitioners to find the roots of stakeholders' disagreements about value judgements. We then generalize the structure of the Worldview Inquiry Framework to produce a "General Inquiry Framework" that can be used to govern an inquiry process in other contexts. We show that the presented Worldview Inquiry Framework is a special case of this General Inquiry Framework and show how the General Inquiry Framework can be tailored for other contexts such as problem solving, product design, and fundamental research.

Keywords: worldview; systems philosophy; Worldview Inquiry Framework; General Inquiry Framework

1. Introduction: Worldviews in the Context of Systemology

Determining and analyzing stakeholder worldviews (also called *weltanschauungen*) is a key step in the methodologies of systems science. Well-known instances are as the "W" in the "CATWOE" analysis technique in Peter Checkland's "Soft Systems Methodology" (SSM), [1] and also as one of the two dimensions of Michael Jackson's "System of Systems Methodologies" (SOSM) [2]. As Martin Hall explained, the power of systems methodologies derive from their taking account of worldviews, because worldviews create the context both for adequate modelling of problems and for appropriate selection of solutions [3].

In the light of the importance of worldviews to systems science and its applications, it is surprising that systems science does not have a canonical[1] model of the structure and dynamics of worldviews, and hence does not provide for a consistent way of working with worldviews across systems theories and methodologies. This shortcoming manifests in at least four ways.

First, different methodologies are not consistent or equally comprehensive about the aspects of worldviews they consider. For example, in SSM the "worldview question" is about what the

[1] If something has canonical status, it is accepted as having all the qualities that a thing of its kind should have (Collins English Dictionary, see https://www.collinsdictionary.com/dictionary/english/canonical).

participants perceive as the value of the project, while in SOSM, it is about the level of alignment between the attitudes of the participants to each other as well as to the project. It is peculiar that the term "worldview" should have both wide and narrow meanings within the discipline of systems science, and it begs the question of whether the methods that employ narrow applications of the term would be improved by taking a broader scope of worldview commitments into account.

Second, specific methodologies can be inconsistent in how they address the same worldview question, drawing out different worldview aspects in different instances. In fact, this even happens across projects in which the same team is employing the same methodology to address the same kind of problem within the same industry sector. An example of this covering five SSM case studies is given in [4]. Also, there are confusions amongst practitioners about what is meant by the "worldview questions" within a methodology, leading to inconsistent or trivial outcomes. This is e.g., discussed in the context of SSM in [5].

Third, "worldview considerations" are often only applied to the participants or stakeholders in the project, while little or no attention is given to the impact on the project of the worldview of the person who is leading the application of the systems methodology. Different systemologists can, depending on their worldviews, associate very different meanings to the same terms, leading to fundamentally different ways of going about selecting and applying a systems methodology. For example, a recent study found that different systems engineers attach different meanings to the term "system," and the differences reflect seven different worldviews [6,7].

Fourth, without a consistent approach to working with worldviews, researchers are free to frame their findings about stakeholder worldviews as they see fit. However, this is problematic because the way in which information is framed can profoundly influence how that information is used. This was already shown in the 1970s, when cognitive psychologists Daniel Kahneman and Amos Tversky applied framing in experimental designs to understand risk judgments and consumer choices, producing Nobel Prize–winning research that concluded that "perception is reference dependent." This research showed that if individuals are reflecting on an ambiguous or uncertain situation then different ways in which a message is presented or framed (e.g., using different terminologies or different visual presentations) can—apart from the content itself—result in very different responses [8].

It has to be acknowledged that this situation is not unique to systems science, and the worldview concept is often applied very narrowly or inconsistently in other disciplines too (e.g., anthropology, sociology and religious studies). For example, "worldview" can be used to refer only to people's religious beliefs, or their moral commitments, or their stances on human rights.

This situation is somewhat understandable. Academic interest in "worldview" as a subject originated in late 18th century philosophy, but remained a minority interest outside of philosophy and theology until the 20th century, when it became important first in psychology (early 20th century) and then from the mid-20th century more widely in areas such as cultural anthropology, religious studies, the social sciences, and epistemology [9]. This wider interest in worldviews therefore only arose in academia around the time of the establishment of systems science as an academic endeavor (ca. 1950), and arguably only become significant in academic discourse in the last decades of the 20th century, notably due the work of Thomas Kuhn on the nature of paradigm change in science (1960s onward) [10,11], and the "science wars" of the 1990s, when differences between scientific realists and postmodernist critics about the nature of scientific theory and intellectual inquiry became prominent in the academic and mainstream press [12].

It can therefore be considered that it is only in the last twenty years or so that academic studies on worldviews have become sufficiently deep, rich, and balanced to form a practical basis for developing a principled worldview model that can be operationalized across the methodologies of systems science.

In our view, a more comprehensive worldview documentation method could help to make systems methodologies more effective and more reliable [13,14].[2] It could also help to expand the use of systems research methodologies into areas currently lacking in systems methodologies, such as frontier science (where the implications of new theories may be challenging to contemporary worldviews) [15–18][3] or social transformation (for example, where technologically driven change is disrupting the worldviews on which contemporary social and political structures and processes depend) [19].[4]

In this paper, we will present a proposal for a thorough worldview framework, based on analyzing and integrating inputs from a range of academic fields. We will argue that our framework represents worldviews comprehensively because it captures the main kinds of knowledge at stake in any scenario. This insight allows us to generalize it into a framework for gathering information in any context where there is uncertainty, risk or ambiguity. The present paper has two main objectives. The first is to present and explain these frameworks as a contribution toward establishing a comprehensive worldview inquiry framework for use in the systems field. The second is to show how this opens the way for establishing a general inquiry framework for use in multiple contexts.

We believe that using frameworks such as these could make systems methodologies more effective, more reliable, and more consistent, and that this will increase the perceived value of systems science in research, design, and intervention.

2. General Background on Worldviews

2.1. The Meaning and Importance of Worldviews

The term "worldview" is the English rendering of the term *Weltanschauung*. The term *Weltanschauung* was coined by Immanuel Kant in 1790 [20] (pp. 111–112), and it rapidly developed as "a term for an intellectual conception of the universe from the perspective of a human knower" [9] (p. 59). The term worldview has a rich academic history, and a dappled application of terminology, which we will not review here. For comprehensive surveys, see [9,21,22].

The term worldview is used differently in different disciplines, typically in each case in order to emphasize a particularly relevant aspect, so that, for example, in management science, "worldview" is typically taken to be about an individual or group's value system, while in theology, "worldview" is often taken to be an individual's view about the existence and nature of God. However, worldviews are richer constructs that these uses suggest. Personal worldviews evolve as people try to integrate their knowledge, experience, and intuitions into a coherent framework they can use to make sense of their lives and make decisions about how to live and what to do [21,23,24]. A worldview, then, is the overall perspective from which one sees and interprets the world in all its diversity and complexity. It functions as a "map of reality" that people use to order their lives [9,21,22,25,26].

In this sense, the scope of worldviews covers all the domains of experience, decision-making, and action and covers all the kinds of information we might have about the nature of the world and our place in the scheme of things.

The general significance of worldviews lies in this: everyone has one, and it constitutes a set of beliefs that guides their judgment making and action taking in all spheres of activity. Different people have different worldviews, and individual worldviews change and develop on an ongoing basis. It is common to find worldview referred to as "a philosophy," meaning a *personal* philosophy. As G.K Chesterton expressed it,

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2 For a discussion of concerns about the success rate and reliability of systems methodologies, see e.g., [13,14].

3 Unexplained phenomena such as consciousness, creativity, intuition, and savant syndrome present clear examples. See e.g., [15–17]. For discussion about the lack of suitable methods for effective frontier research, see e.g., [18].

4 The rising tide if the so-called 'Fourth Industrial Revolution' is clear evidence of the need for methodologies to anticipate and manage social change in the face of technological advances. See, e.g., [19].

> There are some people—and I am one of them—who think that the most practical and important thing about a man is still his view of the universe. We think that for a landlady considering a lodger it is important to know his income, but still more important to know his philosophy. We think that for a general about to fight an enemy it is important to know the enemy's numbers, but still more important to know the enemy's philosophy. We think the question is not whether the theory of the cosmos affects matters, but whether in the long run anything else affects them [27] (pp. 15–16).

Worldviews, or significant portions of a worldview, could be held in common between members of a community, and in this case it is usually referred to as a "paradigm." A familiar example is "the scientific paradigm" as discussed by Thomas Kuhn [10].

2.2. The Complexity and Dynamics of Worldviews

The formation and ongoing adaptation of worldviews is a complex process, in which people integrate knowledge, experiences, and intuitions into a more-or-less coherent whole. The apparent implications of knowledge, personal experiences and intuitions are not always in complete agreement, so this balancing reconciliation is not a simple process, and tends to be under constant revision as more knowledge and experiences are gained. This is an autonomic and largely subconscious process, and for most people, the results are held subconsciously too, so people are typically not explicitly aware of everything in their worldview [25]. This makes it a difficult task in practice to characterize someone's worldview.

Moreover, individual worldviews cannot be classified in a simple way because someone's commitments in one area do not determine (although they do condition) what their commitments might be in another area [28]. For example, someone may be a scientific realist about the material world (i.e., believe that the physical world has an objective existence and we can gain universally valid knowledge about it through science) while being a social constructivist about the nature of values (i.e., hold that values reflect only subjective agreements made within social groups). We will say more about the systemic aspects of a worldview later on, after we have characterized the components of a worldview.

2.3. Paradigms

While a worldview is a personal philosophy, it is usually not completely unique per person. As mentioned above, when a group of people hold a worldview in common then it (or the part of it held in common) is called a "paradigm," and hence we have such designations as the "scientific paradigm," "the Christian paradigm," a "research paradigm," etc. There is a rising interest in paradigms in areas such as peace education, sustainable development, social policy and so on, and from work in these areas, and areas more historically interested in worldviews such as theology, we now have several models in the academic literature documenting paradigmatic worldviews (i.e., types of paradigms and comparisons between their tenets) or paradigmatic approaches to specific worldview components, e.g.:

- A comparison between the paradigms of Traditional, Modern, Postmodern, and Integrative Worldviews [29];
- A comparison between the paradigms of Christian Theism, Secular Postmodernism, Pantheistic Monism, Islamic Theism [30];
- A comparison between different paradigmatic tenets regarding the nature of knowledge, namely from the perspectives of Idealism, Physicalism, Emergentism, Constructivism, Intuitionism, Theism, and Critical Realism [31].

There also now exists good scholarship on the subject of how to develop and validate measures of people's worldview beliefs [29,32] and how to analyze results of such surveys, e.g., to test the coherence of a worldview or to expose their potentials and pitfalls [29,30,33,34].

However, across this academic space, there is substantial variety in what academics identify as the components of a worldview. As we will show later on, there is substantial overlap between different models but also significant differences and omissions. We suppose that to some degree this reflects the interests or motivations of the researchers. Checkland's SSM discussed above provides a case in point, for although the methodology on the face of it claims to be documenting the stakeholder's *weltanschauung*, in fact it only tries to establish what the stakeholder would value in the project outcome. Checkland has confirmed that SSM's "worldview" interest is meant to be narrow in this way [35], but practitioners have suggested that a more comprehensive worldview exploration would improve the quality of the analysis [5].

3. The "Worldview Inquiry Framework"

3.1. Development of the Worldview Inquiry Framework

We have been doing research for several years into the structure and systemicity of worldviews, the concepts employed to frame the tenets that make up a worldview, and how these tenets systemically interdepend. Initially our motivation was to understand how worldviews might be challenged by research findings in frontier science, but as we developed the framework we realized that it might be a useful contribution to all of the fields we have drawn on in developing it, including anthropology, religious studies, social science, theology, cosmology, psychology, philosophy, and systemology, e.g., [9,21,22,25,29,30,34,36–49]. We realized early on that systemology would provide a natural home for our work in this area, because:

- a worldview is a system and hence is most appropriately studied from a system perspective;
- systems science and systems thinking contain many methodologies for which consideration of aspects of worldviews is essential irrespective of the problem context, so systemology provides an active and diverse community with whom to engage; and
- systemology is a transdiscipline, and hence it is part of its objectives to develop tools that can be applied across disciplines and contexts.

In order to develop our understanding of the structure, systemicity and conceptual terrain of worldviews, we drew extensively on philosophical literature (especially ontology and metaphysics) to find ways of reconciling different uses of the same terms (e.g., what is meant by terms such as existence, purpose, God, matter, value, etc.). From the outset, we were convinced that it would be possible to arrive at a usefully consilient outcome, despite the diversity of perspectives, terminologies, and purposes presented in the academic literature on worldviews. Over the period of our study, we and our collaborators presented various aspects or early models of our emerging perspective on worldviews in publications, workshops, seminars, and conference presentations, e.g., [28,31,50–59]. In this paper, we bring together, and extend, the high-level findings of this research programme. We were also able to generalize our approach to exploring worldviews to create a framework for exploring information categories in other scenarios, which we have presented in a paper and a workshop [60,61] that inspired two case studies, the results of which are scheduled for presentation at two upcoming conferences [62,63].

3.2. High-Level Overview of the Worldview Inquiry Framework

We now present, at high level, our Worldview Inquiry Framework in Table 1. Each row illustrates aspects of one component of a worldview. In the first column, we provide our recommended categories for the components of a worldview. This choice of categories was driven by the need to separate the components in a clear way while remaining as close as possible to the divisions suggested by other researchers [64].[5] Please note that the terms used for these categories have multiple meanings in standard usage. For example, "axiology" typically refers to a philosophical discipline concerned with the nature of values, investigating what values are, how they arise, how they are applied, and what their criteria of merit are. Against this, a particular person may have various "axiological beliefs" that represent their personal value system and beliefs about what an appropriate grounding for a value system is. This set of beliefs then forms that person's "axiology," i.e., the values-related component of their personal philosophy. This latter sense of the term is intended in Table 1, but it should usually be clear from the context how the category terms are to be understood.

The second column illustrates the kinds of questions that are the focus of each worldview category, and column 3 gives an overview of the scope of the inquiry in each category. To frame appropriate questions and relevant beliefs one needs appropriate concepts, and we give some examples for each category in column 4. The aim of an inquiry into worldviews is to explore the beliefs a person holds in each category, and we give some examples of possible answers one might receive in column 5. Note that these are illustrative examples only and are not a set meant to represent any specific worldview, and we do not intend with these examples to recommend some beliefs over others. For example, in row 4 (cosmology of nature), the illustrated belief that physical nature arose via the Big Bang and has since evolved naturalistically is one possible option for a belief about the origin and history of nature, but others options also exist e.g., the belief that physical nature was created by and is unfolding under the governance of God, or that physical nature is an illusion arising within a personal or universal consciousness, or some combination of such beliefs. The plausibility or coherence of alterative options are not here at stake, and can only be assessed in the light of beliefs in other components (e.g., epistemological commitments about what counts as authoritative sources of knowledge and why).

Note that, from an information-gathering perspective, the logical sequence in which the components are addressed can be rearranged to suit the context, so there is no special significance to the sequence of the rows in Table 1. For example,

- for systemic intervention, the system practitioner might be primarily interested in what stakeholders value, in which case the analysis will start with axiology;
- for teamwork, the leader might be interested in each member's perspective on their role in the team, so would start their inquiry with praxeology; and
- for frontier research, the scientist might be primarily interested in how new theoretical insights might impact the scientific paradigm and hence would start their inquiry with ontology or metaphysics.

Note also that the extent to which information needs to be gathered in any area depends on the needs of the particular inquiry. The framework provides a guide to options, but it is not obligatory to pursue them all. For example, in a systemic intervention, different stakeholders may have different reasons for considering a project important, but these may not be in conflict with each other, in which case, the project can proceed in a consensual way (e.g., in a railway project the same solution can provide both jobs for the locals and a low-carbon transport system for the economy). However, if the stakeholder values are conflictual, then the inquiry will have to "dig deeper" in order to expose the roots of the conflict and mediate a resolution (e.g., in a railway project, the environmental harm of building the railway system must be reconciled with the social benefit of the project).

[5] The most controversial case is the ontology/metaphysics split. In the philosophical literature, some academics regard the ontology/metaphysics division as superfluous and settle for just the one or the other, some regard ontology as a subset of metaphysics, some regard metaphysics as a subset of ontology, and some regard the split as meaningful but only one of the two to be a feasible undertaking. For an accessible discussion, see [64]. A basic illustration of the possible distinction is this: the claim that "gravity" exists, and claims about what its identifying features are, are ontological claims; claims about the nature of gravity (e.g., that it is a force field or a curvature in space) are metaphysical claims.

Table 1. A framework for cataloguing the components of a worldview.

Worldview Component	Key Question	Content Scope	Relevant Concepts	Examples of Worldview Commitments
Ontology	What kinds of substances exist most fundamentally? What grounds the existence of reality?	Theory about what exists most fundamentally; Models of identifying characteristics	Space, time, matter, minds, God, Akasha, Apeiron, consciousness	All concrete things are physical particles or composites of them
Metaphysics	What is the nature of the fundamental existents?	Theory about the powers, limitations and dynamics of what exists (and hence what is possible given the ontology)	Energy, lawfulness, real/imaginary, concrete/abstract, natural/supernatural	An objective reality exists; All changes have lawful causes
Cosmology I (Cosmology of Nature)	What is the nature, origin, developmental history and potential of the natural world?	High-level theory about the origin, history, current state & activity, future and destiny of nature	Big bang, creation, evolution, systems hierarchy, expansion, heat death, transcendence	The world arose at the Big Bang and evolves in accordance with naturalistic laws.
Cosmology II (Cosmology of Persons)	What is the nature, origin, developmental history and potential of human beings?	High-level theory about the origin, history, current state & activity, future and destiny of human beings	Evolution, reproduction, development, sentience, memory, will, agency, freedom, rationality, cognition, judgement, intentionality, wisdom	Human beings are animals with sentience, free will, agency, rationality, rights and duties
Axiology	What is important and why? What makes something 'good'?	Theories about what is good or important and why	Values, ethics, morality, aesthetics, social construction, utility theory, natural law theory, divine command theory	All sentient beings have the right to life and freedom
Praxeology	How should we live? What gives action meaning? What are our purposes and how can we achieve them?	Theories about what is meaningful or purposeful action and why. Action principles and theories about agency, freedom and responsibility	Free will, choice, agency, freedom, responsibility, duty, best practice	We are responsible for our choices and our actions
Epistemology	What/how can we (not) know?	Theories about what kinds of knowledge are possible and how to gain knowledge	Science, sacred texts, cultural authority, intuition, mystical revelation, experience	The scientific method can progressively reveal the truth about all real phenomena

3.3. Comparison with Other Worldview Models

With the clarifications given in Table 1 in mind, we can now compare the Worldview Inquiry Framework with representative examples of other worldview frameworks, as given in Tables 2 and 3. We have selected only proposals with a reasonably rich structure, each containing at least five components. Most literature sources discuss only 1–3 components. For reasons of space, we present the comparative data across two tables, and align them by repeating the first column. As will be seen in Table 2 Part 1 and Part 2, the other worldview framework proposals map fairly well onto the components and questions of the Worldview Inquiry Framework but are not as comprehensive. For reference purposes we list in the first row the name of the author, the key years of publication of their framework, a citation of the key publication, their description of what their framework is about (in curly brackets), and the discipline they are from (in triangular brackets). Where authors have categorized their worldview questions, we report their category labels. Sometimes, their questions under one label span several categories of our framework, and in such cases, we split their categories and numbered the segments to indicate the fragments. Where authors have numbered their own subdivisions, we use their numbering (a case in point is de Witt et. al. in Part 2 column 4).

Note to Table 2 Part 2: The questions reported in Column 4 for the Integrative Worldview Framework (IWF) are paraphrased by us to represent what we take to be the intent of groups of survey questions in the IWF. We formulated this paraphrase to enable comparison with other frameworks, but we acknowledge that de Witt et al. might summarize the intent of each question set differently. In the other columns of Table 2 (Parts 1 and 2), we use the researchers' own expressions in posing their questions or propositions.

The comparisons given in Table 2 demonstrate that the other frameworks are subsets or special cases of our proposed framework and hence that our framework could stand in for any of these other application areas. On this basis, we conclude that our proposed worldview framework is comprehensive in scope, and hence would be suitable for use in any context where worldviews, or aspects of worldviews, are at issue.

3.4. An Extended Worldview Inquiry Framework

To make the Worldview Inquiry Framework easier to use, it is helpful to expand each component into subsections under which related questions can be grouped. To frame appropriate questions, and document their answers, specific concepts are needed, and it would be helpful to develop a standard set of concepts so this work can be done in a consistent way. We make a first proposal along these lines in Figure 1, where we use the Worldview Inquiry Framework to give structure to a concept map that identifies some of the relevant concepts in each area. Further work is needed to refine the concept lists and disambiguate each concept, and we elsewhere discuss a methodology for doing such work [66]. This is an important task still to be done, because as mentioned in the Introduction, it is known that presentation format and terminology affect how people respond to information even beyond the content of the information.

As we noted above, there are good methods already present in academia for developing worldview questions, validating the survey instruments and analyzing the interview results. What was lacking, in our view, was

- a comprehensive but succinct framework on which to base such surveys;
- a consistent set of concepts for formulating worldview questions and documenting beliefs.

The tools we have introduced so far in this paper are offerings toward closing these gaps.

Table 2. A comparison of different proposals for cataloguing the components of a worldview.

Part 1				
Rousseau & Billingham (2018) {*The Worldview Inquiry Framework*} **<Systems Philosophy, Science>**	**Ken Funk (2001)** [40] {*The elements of one's worldview*} **<Engineering>**	**Clement Vidal (2008)** [38] {*Fundamental questions, and the disciplines that try to answer them*} **<Evolutionary Cosmology>**	**James Sire (1976, 2004)** [22,36] {*Questions every worldview should answer*} **<Theology>**	**Diederik Aerts et al. (1994)** [39] {*The components of a worldview*} **<Physics>**
Ontology (What exists to generate the world? What provides the conditions for the possibility of the existence and nature of the world?)	Theology 1: beliefs about the existence of God	What is? (Ontology—model of reality as a whole)	What is prime reality—the really real?	-
Metaphysics (What is the nature/character of the fundamental existent(s)?)	Metaphysics: beliefs about the ultimate nature of Reality Theology 2: beliefs about the nature of God	-	What is the nature of external reality, that is, the world around us?	Why is our world the way it is, and not different? Why are we the way we are, and not different?
Cosmology I (Cosmology of Nature) (What is the nature of nature? What is its origin, scope, history and potential?	Cosmology: beliefs about the origins and nature of the universe; Teleology: beliefs about the meaning and purpose of the universe, its inanimate elements, and its inhabitants	Where does it all come from? (Explanation—model of the past) Where are we going? (Prediction—model of the future)	-	What is the nature of our world? How is it structured and how does it function?
Cosmology II (Cosmology of Persons) (What is the nature, origin, history and potential of persons?)	Cosmology: beliefs about the origins and nature of life and Man;	-	What is a human being? What happens to a person at death?	What future is open to us and our species in this world? By what criteria are we to select these possible futures? How, in what different ways, can we influence the world?
Axiology (What is important and why)	Axiology: beliefs about the nature of value, what is good and bad, what is right and wrong	What is good and what is evil? (Axiology—theory of values)	How do we know what is right and wrong?	-
Praxeology (How should we act and why)	Anthropology: beliefs about the nature and purpose of Man in general and, oneself in particular	How should we act? (Praxeology—theory of actions)	What is the meaning of human history? What personal, life-orienting core commitments are consistent with this worldview?	How are we to act and to create in this world? What are the general principles by which we should organise our actions?
Epistemology (What can we know? How and why?)	Epistemology: beliefs about the nature and sources of knowledge	What is true and what is false? (Epistemology—theory of knowledge)	Why is it possible to know anything at all?	Why do we feel the way we feel in this world, and how do we assess global reality, and the role of our species in it? How are we to construct our image of this world?

Table 2. *Cont.*

Part 2				
Rousseau & Billingham (2018) {*The Worldview Inquiry Framework*} **<Systems Philosophy, Science>**	**Ninian Smart (1981) [37]** {*Dimensions of every religious worldview*} **<Religious Studies>**	**Mario Bunge (2009) [65]** {*The branches of an authentic philosophy*} **<Scientific Philosophy>**	**Annick De Witt et al. (2016) [29]** {*The aspects of 'The Integrative Worldview Framework'*} **<Sustainable Development>**	**Kenneth Samples (2007) [30]** {*The major components of a worldview*} **<Theology>**
Ontology (What exists to generate the world? What provides the conditions for the possibility of the existence and nature of the world?)	Doctrinal or philosophical dimension	Ontology 1: being	-	Theology—Concept of God, or absence of such
Metaphysics (What is the nature/character of the fundamental existent(s)?)	Doctrinal or philosophical dimension	Ontology 2: becoming	Ontology 1—Metaphysics: What is the nature of reality?	Metaphysics—View of external reality, especially the cosmos
Cosmology I (Cosmology of Nature) (What is the nature of nature? What is its origin, scope, history and potential?	Narrative or mythical dimension	-	Ontology 3: How did life originate? Ontology 4: What is the nature of nature?	History—Study of the nature, direction and purpose of unfolding historical events
Cosmology II (Cosmology of Persons) (What is the nature, origin, history and potential of humans?)	Narrative or mythical dimension	-	Anthropology 1, 2, 3, 6: What defines who I am? What is a human being? What the humans' relationship to nature? What happens to us at death?	Anthropology—Study of the origin, nature, problems and destiny of human beings
Axiology (What is important and why)	Ethical or legal dimension	Axiology: values; Ethics: rights and duties	Ontology 2—What is the value of nature? Axiology 1, 2: What is important to me? What motivates my attitudes? Anthropology 4: What rights and obligations do we have about nature? Societal vision 1, 2: What is our role in society? What are our rights and duties in society?	Axiology—Study of the origin, nature, meaning and criteria of values
Praxeology (How should we act and why)	Ritual or practical dimension; Social or institutional dimension	Praxeology: action	Axiology 3, 4: What do I value in life? What is my preferred lifestyle? Anthropology 5: Why do we suffer?	
Epistemology (What can we know? How and why?)	Experiential or emotional dimension	Epistemology: cognition and knowledge; Logic: precision and deducibility; Semantics: meaning and truth; Methodology: evidence; Philosophy of Science	Epistemology 1, 2, 3: What is the role of science? What are the impacts of science and technology? Who/what can I trust about what to believe?	Epistemology—Study of the origin, nature, limits and validity of knowledge

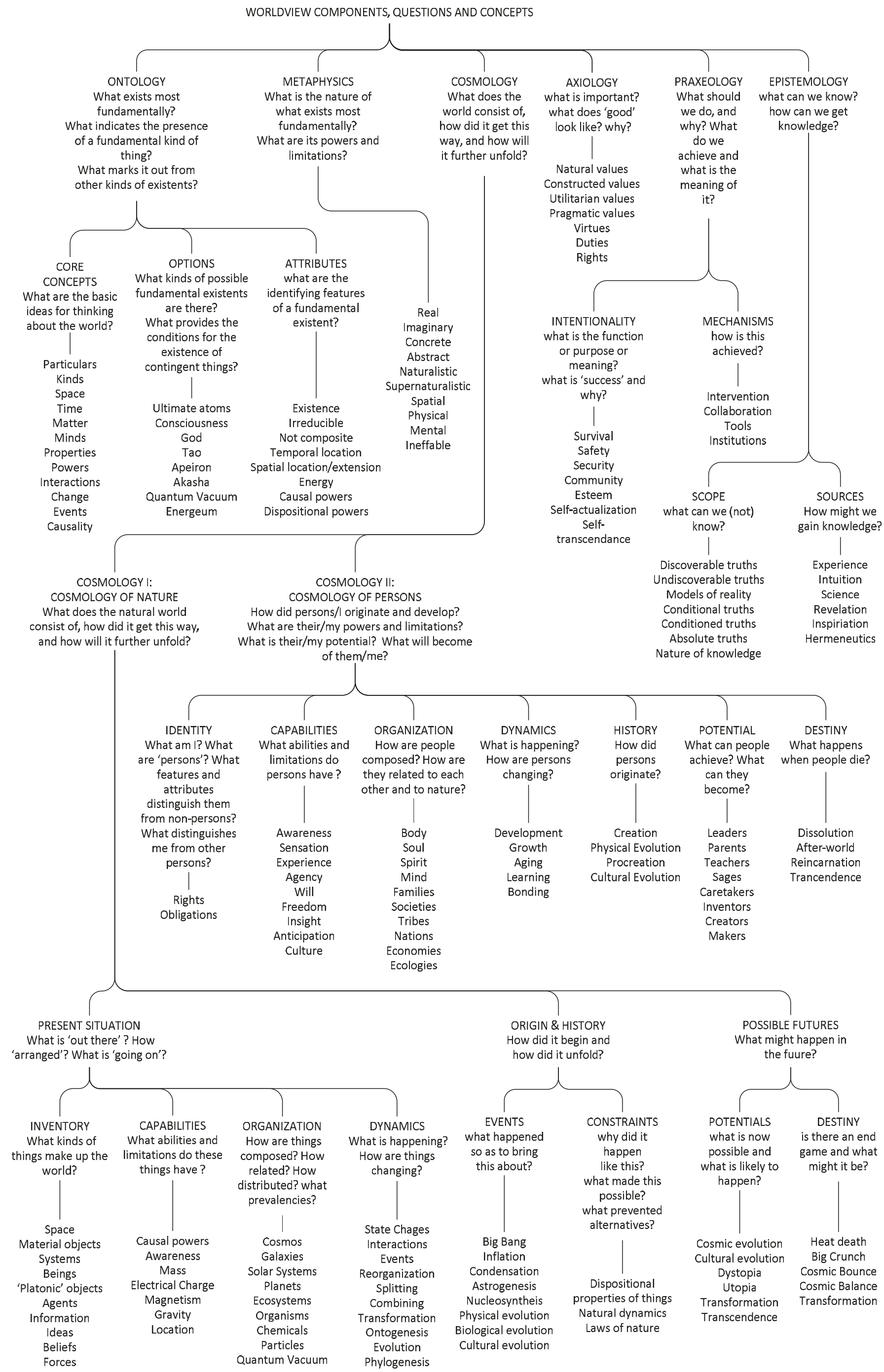

Figure 1. An extended Worldview Inquiry Framework and a mapping of relevant concepts.

4. The World as a System, Modelled in Terms of the Worldview Inquiry Framework

We earlier mentioned that worldviews are systems without defending or exploring that assessment. However, now that we have defined the components of a worldview and their correlated areas of belief, we can return to consider the nature and the implications of the systemicity of worldviews in more detail.

According to one systems definition, due to Anatol Rapoport and popular in the systems science community, a system as a whole that functions as a whole because of the interactions between its parts [67]. This is consistent with the definition of systems now emerging in the systems engineering community, according to which "A physical system is a structured set of parts or elements, which together exhibit behaviour that the individual parts do not" and "A conceptual system is a structured set of parts or elements, which together exhibit meaning that the individual parts do not" [6,68].

In the sense of these definitions a worldview is a conceptual system. A worldview's systemicity is evident in the way that the content of the components of a person's worldview change not only to accommodate new information but to strive toward coherence—that is, to make sense as a whole. It is also evident on a larger scale, where, as Thomas Kuhn explained, paradigm shifts occur when the coherence of a current paradigm (a worldview shared by a group) cannot be maintained given cumulative new evidence and current beliefs, and hence a shift to a new balance is triggered. This happens via a "revolution" that adjust beliefs so as to incorporate the new evidence in a way that allows the overall set of adjusted beliefs to come back into coherence as a whole [10].

Of course, a worldview is not only a conceptual system but also a "map of reality," a view on the actual world, which (at least under the perspective of scientific realism) is a system also, and a worldview is a model of the structure and coherence of the concrete world, in the sense of Robert Rosen's "modelling relationship" [69].

It is instructive to sketch a "systems model" of the world in terms of the components and interdependencies of the Worldview Inquiry Framework proposed earlier. In Figure 2, we present a diagram that shows one way of illustrating some of the correspondences between the components of a worldview (right hand side) and the aspects of the world that they represent (left hand side) together with some of their interdependencies (linking arrows).

This is not a unique or a comprehensive model of the systemicity of the world, but it is sufficient for illustrating the basis of the implications we draw out below.

Recognizing that worldviews are conceptual systems and that they model a systemic world, and being able to provide a comprehensive framework for representing this, are valuable advances for two reasons.

First, the structure of the model tells us something important about how worldviews underpin people's behavior. We can see here that actions depend on judgments, which in turn depend on values. Values depend on beliefs about the nature of people and the world, natures that are manifested via their powers and limitations. The existence of people and the world, and their powers and limitations, depends in turn on the types and natures of ultimate substances. The implication is that people's values depend deeply on their ontological and metaphysical beliefs. This is clearly seen in how people's assessments of the meaning of their lives and their actions vary depending on whether they consider "ultimate reality" to be, e.g., physical matter, or consciousness, or an alien simulation programme, or God. From a scientific perspective the nature of "ultimate reality"is far from settled, and hence we have ongoing controversies and conflicts about meanings, rights, and duties across different stakeholder communities. This underscores the importance of current research into these "frontier areas" [50,70–72]. For the moment, though, understanding the dependencies among components of a worldview is important for systems practitioners because, in the case of conflicts between stakeholder perspectives, it enables the practitioner to trace the roots of those differences via these dependencies, and hence places the practitioner in a position to facilitate a conversation between the stakeholders to bring about convergence of or at least mutual understanding or respect for these differences.

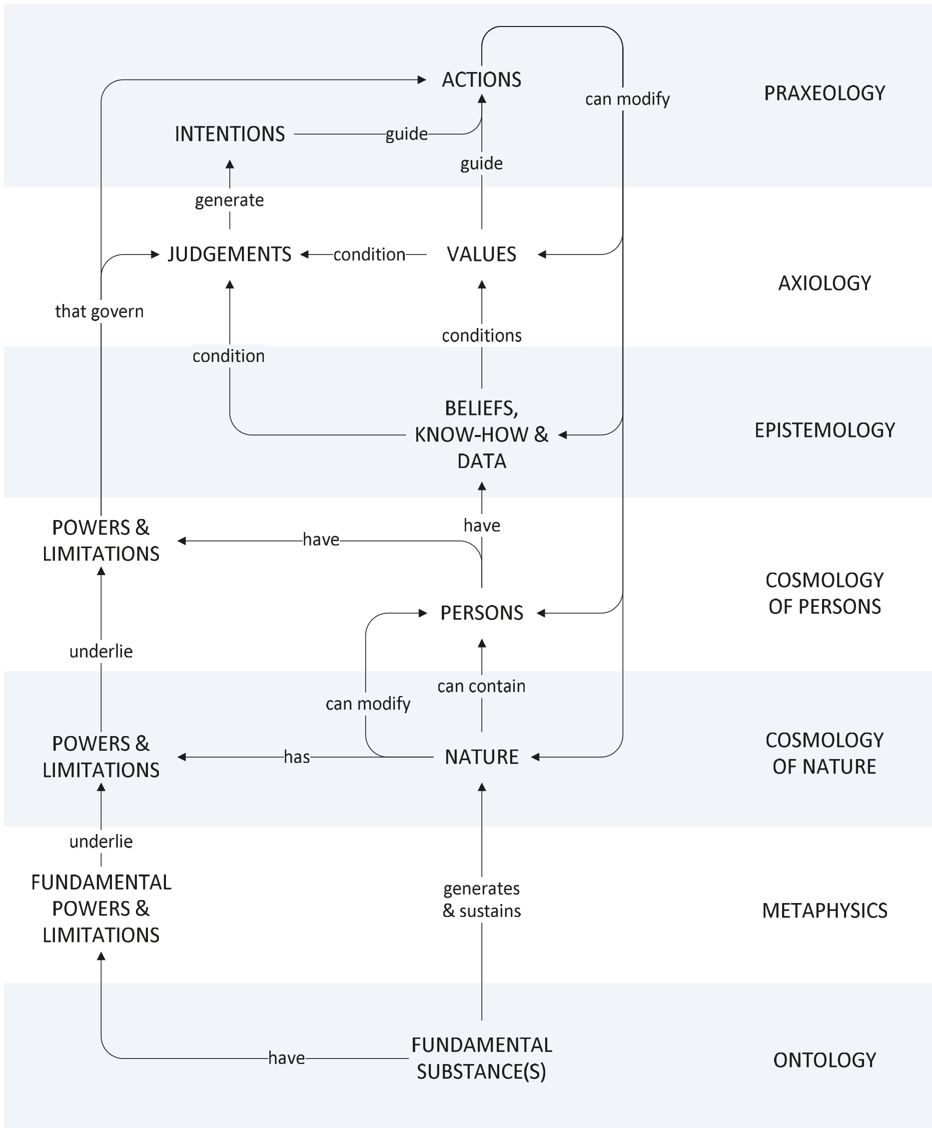

Figure 2. A systems model of the world from the perspective of the Worldview Inquiry Framework.

Second, the systemicity of worldviews holds important lessons about the dynamics of worldview change, e.g.,

(a) Because the worldview system strives towards coherence, we can understand the reasons for the stability of worldviews—their systemicity entails that they would resist incorporation of ideas or beliefs that do not fit in in a way that preserves the existing (approximate) coherence.

(b) We can understand why paradigm shifts are so rare and so dramatic. Being a deep conviction held by a group, paradigmatic worldviews are even more stable and resistant to change than individual worldviews. When the total body of available and credible (but worldview challenging) evidence becomes too large to easily ignore or credibly reject, and so *has* to be incorporated, the systemicity of the worldview/paradigm ensures a 'ripple effect', so that change propagates throughout the worldview/paradigm *system* to establish a new balance that renders the whole coherent again (as described in Thomas Kuhn's works [10,11]).

(c) From a systems point of view, the last point explains why paradigm change is the most powerful leverage point for bringing about change for a group, as proposed by Donella Meadows [73].

5. The "General Inquiry Framework"

5.1. Generalizing the Worldview Inquiry Framework

The Worldview Inquiry Framework can be generalized to produce a multi-purpose inquiry framework in the following way.

A worldview that is adequate for guiding a person though all life's potential scenarios will have to contain beliefs about every aspect of reality. According to the Worldview Inquiry Framework, there are six kinds of beliefs in a worldview (not seven, because the Worldview Inquiry Framework divided cosmological beliefs into two aspects). This entails that there are six aspects to reality, each of which one could have beliefs about. Knowledge is "warranted true belief," i.e., a belief counts as knowledge if it is believed, if what is believed is true, and if it is believed for valid reasons (a belief that is accidentally true is not knowledge). A worldview can contain many beliefs that do not count as knowledge, but relevant knowledge will always fit into a worldview. From this we can infer that there are potentially six kinds of knowledge one could have about reality, or any subset of reality, and thus potentially six kinds of knowledge one could seek about any actual situation. In this way we could envision a general framework for organizing knowledge about anything, or any scenario, based on the six categories employed in worldview beliefs. This suggests that we could inquire after these kinds of knowledge by posing general questions framed after the manner of the ones used in formulating a worldview. Having noted this possibility, we proceeded to devise a generalization of the Worldview Inquiry Framework, producing what we call the "General Inquiry Framework." We explain it below and then show how it can be tailored for application in different contexts such as problem solving, product design, and foundational research.

5.2. General Questions for a General Inquiry Framework

We develop this framework in two stages. The first step is generalize how the worldview component names are interpreted, so they reflect the kind of information that is at stake, rather than kinds of beliefs or kinds of disciplines. Most remain unchanged as terms except for the clarifications of the 'cosmology' terms. In a worldview, the primary concern is centered on the person whose worldview is at stake, for whom the worldview answers how they should live. The person and their nature, history and potential is therefore, in general terms, the "subject of interest" in a worldview (Cosmology II). To work out the foundations of the person's purpose and motivation, the worldview tries to work out the place of the person in "the grand scheme of things", that is to say, in general terms, their "context" (Cosmology I). Once we generalize by seeing the person as a special case of a "subject of interest" and their place in the world as a special case of the "context" of a subject of interest, we can generalize all the other categories, as shown in Figure 3. Apart from the subtext of Cosmology I and II the other terms are retained as they were but their focus is slightly altered, as made clear by insertions in brackets after the component labels and the forms of the questions following. The main change here is that, having established the categories of "Cosmology of Subject of Interest" and "Cosmology of Context", we can now recognize that both these categories are grounded in a more general "Area of Interest", which provides us with the foundational concepts needed via answers to ontological and metaphysical questions. The other terms are retained as they were but their focus is slightly altered, as made clear by insertions in brackets after the component labels and the forms of the questions following.

The main change here is that, having established the categories of "Cosmology of Subject of Interest" and "Cosmology of Context", we can now recognize that both these categories are grounded in a more general area of interest, which provides us with the foundational concepts needed via answers to ontological and metaphysical questions. For example, if a scientist were to take "salamanders" as their subject of interest, and hence aquatic environments as "context", the "area of study" would be characterized by the core concepts of *biology*, as characterized by "biology's ontology" (broadly, answers to the question "what variety of biological entities exist and how are they identified?") and "biology's metaphysics" (broadly, answers the question "what are the powers and limitations of kinds of biological entities?").

Note that, as discussed before in the context of the Worldview Inquiry Framework, the context of the inquiry will determine in what sequence the inquiry components are addressed, and to what depth any component is explored.

Worldview Inquiry Component		General Inquiry Component	Typical Information Component Questions
Ontology	→	**Ontology** (of area of interest)	What are the fundamental existents or fundamental categories of thought for our area of interest? What variety of things occurs in the area of interest? What features and attributes identify them?
Metaphysics	→	**Metaphysics** (of area of interest)	What is the nature of the entities contained in the area of interest? What are their generic powers and limitations? What powers are unique to these entities?
Cosmology I (cosmology of nature)	→	**Cosmology I** (cosmology of context of subject of interest)	What is present in the context or environment of the subject of interest? What are the capabilities of those entities? How are they organized? How did that scenario come about and how will/could it change? What are the relationships between the specific subject and its context? How do they condition each other?
Cosmology II (cosmology of persons)	→	**Cosmology II** (cosmology of subject of interest)	What specific or specialised thing is the particular subject of interest? What are its defining attributes? How did/could the subject of interest originate? How did/could it develop into its present/desired state? How might/should it change in the future, and what will/could become of it?
Axiology	→	**Axiology** (of subject of interest)	What is the importance or value of the specific subject of interest's existence and behaviour? Why does it matter what it does?
Praxeology	→	**Praxeology** (of subject of interest)	What functions can the specific subject of interest perform? What is the meaning or purpose or relevance of its activities? By what mechanisms are these outcomes achieved?
Epistemology	→	**Epistemology** (of area of interest, and of the specific subject of interest and its context)	What can we know about the subject of interest and its context? What methods can reveal this information? How can we assess the comprehensiveness and credibility of this information?

Figure 3. Components for a General Inquiry Framework, based on worldview components.

Table 3. Inquiry framework questions specialized for different contexts.

Inquiry Framework Component	Questions for Documenting a Worldview	Questions for Designing a Product ("X")	Questions for Solving a Problem ("Y")	Questions for Investigating a Phenomenon ("Z")
Ontology (of area of interest)	What kinds of substances exist most fundamentally? What grounds the existence of reality?	What variety of products exists in our area of interest? What are their distinctive attributes? What lies outside our area/remit?	What variety of problems exists in our area of interest? What are their distinguishing attributes? What problems are not for us to worry about?	What variety of fundamental existents is presumed to exist in our area of study? Where is the boundary of our area of concern?
Metaphysics (of area of interest)	What is the nature of the fundamental existents?	What is the nature of the things in our area? What are the powers and limitations of things in our area of interest?	What is the nature of the problems in our area? What effects do they have? What are the limits of their influence?	What is the presumed nature of the fundamental existents in our area? What are their presumed powers and limitations?
Cosmology I (cosmology of context of subject of interest)	What is the evolutionary history and potential of the natural world?	What context creates the need for X? Who are the stakeholders? What s the environment in which X will operate? How will the presence of a X change its environment and vice versa?	What is the context in which Y occurs? What is the relationship between Y and its environment? How might different solutions change the future context?	What is the context in which Zs arise? What is its relationship to its environment?
Cosmology II (cosmology of subject of interest)	What is the scope, origin, developmental history, and potential of human beings?	What specific kind of thing ("X") are we asked to make? How can we create Xs? How can we sustain them? What can become of them?	What is the scope of our specific problem ("Y")? How did it arise and unfold? What will happen if we do not intervene? What about Y can we change?	What is the nature of the phenomenon under study? Where does it occur? How does it originate and develop? What is its potential?
Axiology (of subject of interest)	What is important and why? What makes something 'good'?	Why should the X be like that? How may be (not) develop/ produce it?	Why is Y perceived as a problem? Who are the stakeholders what are their values?	Why does it matter what Zs are and do? How may we (not) investigate it? What value can we derive from understanding it?
Praxeology (of subject of interest)	How should we live? What gives meaning to our actions? How can we achieve meaningful actions?	What should the desired system do/achieve? What mechanisms could produce that? What methods do we have for designing such a thing?	What actions or outcomes would resolve the problem? What mechanism should we remove, adjust or install to achieve the desired outcome? How can we get this done?	Why do Zs do what they do? What functions do its behaviours provide? By what mechanisms are the functions attained?
Epistemology (of area of interest, and of the specific subject of interest and its context)	What/how can we (not) know?	How could we know that X solves the actual problem at stake? How can we know that X will or does function as intended? What confidence can we have in this knowledge?	What/how can we learn about Y? How can we know the potential consequences of an intervention? How confident can we be in our understanding of Y and the consequences of our intervention?	How can we gain understanding of Zs? What methods are effective?

5.3. Adapting the General Inquiry Framework for Different Contexts

From Figure 3, it is now clear that the Worldview Inquiry Framework is a special case of the General Inquiry Framework, where the subject of interest (Cosmology II) is a person, the context of the subject of interest (Cosmology I) is everything in nature (which includes social and cultural systems), and the area of interest (Ontology) is ultimate reality (what some refer to as "the ground of being").

With the General Inquiry Framework in mind, we can now propose specialized kinds of questions to be asked in specific alternative scenarios, as shown in Table 3, adapted from the general questions given in Figure 3.

The specialized varieties of the General Inquiry Framework in Table 3 are illustrative only, and not meant to be exhaustive. However, given this example, an investigator could expand these examples or tailor the General Inquiry Framework for other scenarios.

It should be noted that multiple tailored inquiry frameworks could be applied in the same project. For example, a project may at the outset implement a Problem-Solving Inquiry Framework but then apply the Worldview Inquiry Framework to the stakeholders in that scenario and use a Product Design Inquiry Framework to explore potential contributions to a solution.

6. Conclusions

In this paper, we propose a comprehensive "Worldview Inquiry Framework" that can be used across research contexts where knowledge of worldviews is important. We discuss the systemicity of worldviews, and explain how this can help practitioners to find the roots of differences between stakeholders' perspectives. We propose a generalization of the Worldview Inquiry Framework to produce a "General Inquiry Framework" that can be used to guide an inquiry process in other contexts and illustrate how the general inquiry questions can be tailored for contexts such as worldview analysis, problem solving, product design, and fundamental research.

Author Contributions: The project was conceived and managed by D.R. J.B and D.R. contributed equally to the research and writing of the text. D.R. drew the diagrams.

Funding: Financial and material support for the project was provided by the Centre for Systems Philosophy, INCOSE and the University of Hull's Centre for Systems Studies.

Acknowledgments: We would like to thank Javier Calvo-Amodio and the attendees of our workshops and seminar events for useful discussions in developing the arguments presented in this paper. We are also grateful to two anonymous reviewers of this paper for their helpful comments, which have greatly aided us in improving the structure and clarity of this paper.

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

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Maturity Models for Systems Thinking

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Received: 27 March 2018; Accepted: 31 May 2018; Published: 11 June 2018

Abstract: Recent decades have seen a rapid increase in the complexity of goods, products, and services that society has come to demand. This has necessitated a corresponding growth in the requirements demanded of organizational systems and the people who work in them. The competence a person requires to be effective in working in such systems has become an area of increased interest to scholars and practitioners in many disciplines. How can we assess the degree to which a person is executing the competencies required to do good systems work? Several industries now utilize maturity models in the attempt to evaluate and cultivate people's ability to effectively execute complex tasks. This paper will examine current thought regarding the value and pitfalls of maturity models. It will identify principles and exemplars that could guide the development of a Maturity Model of Systems Thinking Competence (MMSTC) for the varied roles people inhabit in systems contexts.

Keywords: systems thinking; competence; maturity models

1. Introduction

There are many aspects of systems science that occupy the minds of its practitioners. Increasing the widespread use of high-quality systems thinking is among them. Enthusiasm for this goal is based on the conviction that thinking systemically and applying systems knowledge to critical issues are of evolutionary significance to our world. Fueled by this conviction, the systems body of knowledge is growing, being codified, and evaluated for its progress in occupying a rightful place among other scientific disciplines.

Recent work on systemology (e.g., [1,2]) is working to formalize systems knowledge so that educational efforts can give people "clear concepts and a common language that gives them the capability to articulate and reflect on this (systemic) sensibility, and act upon it in a considered way" [3] (p. 3). Further, formalization and other efforts to increase the quality of systems knowledge can enable systems thinkers to "gain influence in supporting organizations, and through that influence to better enable systems thinking and acting of individuals and groups, which may (in turn) lead to more quality in how people deal with complex challenges" [3] (p. 5). At a macro level, the systemology initiative is working to organize our understanding of the body of knowledge about systems relative to other scientific disciplines and to identify key gaps in that body of knowledge.

At a micro level, individual people who consciously work with systems inhabit varying roles—systems engineers, systems scientists, systems dynamicists, and systems practitioners among them. People in each of these roles deal with varying issues and situations and therefore face varying technical demands; a great range of systems competencies is required for the different roles that systems workers play. Future research would be useful to identify the range of roles people do play with respect to systems to clarify the characteristics of the varied personae they require to do systems work. The present paper addresses a different matter. Alongside the ongoing macro-level work to identify the maturity of the systems body of knowledge, there is a need to address, at a more micro level, the levels of competence required for systems thinkers to be effective.

From a "resource-based view of the firm" [4], the unique competencies of people are a resource as crucial as the combination of capital, physical, and other tangible resources that make up a human system. Measuring competence levels, it is reasoned, should be as important to an organization as measuring operational efficiency or financial performance [5]. In business, things get measured so that action can be taken to manage and improve them. Increasingly, this premise is being applied to the degree of maturity that an organization's people exhibit, i.e., the degree to which they are applying the knowledge and behaviours necessary to achieve excellence. There is increasing interest in identifying reliable ways of measuring such competence. Without the ability to reliably measure competence, it is difficult to strategically focus organizational attention to things such as "staff development, recruitment and selection, professional registration, training needs, analysis and planning, job descriptions, assessment and appraisal" [6] (p. 16). Without this measurement ability, pragmatic action to increase competence maturity is difficult to take.

From the academic standpoint, Rašula, Vukšić, and Štemberger have noted that without reliable ways to measure competence maturity, "a comprehensive theory of knowledge or knowledge assets is very difficult to develop. Consequently, there is no visible progress in the effort to treat knowledge as a variable to be researched, or asset to be managed" [5] (p. 48). The argument here is that maturity assessment is important in developing a common understanding of what comprises fundamental concepts such as *knowledge* and *development*. Creating a maturity assessment demands "refinement of a general, unified representation" of such concepts across specialties [7] (p. 83), which can enable consistency in communicating and operationalizing these ideas. These considerations, arising from organizational theory, are relevant to the issues identified by the editors of this special issue on systems thinking. Without reliable ways to measure the maturity of anyone's competence in systems thinking, it is difficult to develop a theory of systems knowledge. It is difficult to argue for the treatment of systems thinking as an asset for an individual, an organization, a profession, or an academic discipline. It is difficult to agree on how to define exactly what is systems thinking and difficult to know how to develop it.

We can consider another difficulty. The presence of maturity models can assist the development of a comprehensive theory about systems thinking. At the same time, a comprehensive theoretical foundation would be invaluable in developing a maturity model. Which should come first: models of systems thinking maturity, or theories about systems thinking maturity on which models could be based? Perspectives on how such efforts should be sequenced differ according to stakeholder group. Businesses want to focus on what is known about success, what works, and what can be improved. They want models that enable employees to take pragmatic action on present-day demands. They do not have the luxury to await fully developed theories and formalized knowledge before action can be taken. Yet, given the pressing nature of many of the problems to which systems thinking is being applied, undertheorized systems thinking also seems to be a risk. Here, the academic community can help to mitigate the risk, clarifying knowledge and other relevant constructs, thus helping industry to have confidence in the validity of what gets measured and is believed to create success. Scholarly efforts can improve the advancement of science (while also complementing business' concerns) by focusing on the development of understanding while being less constrained by demands for short-term focus and commercial profitability [8]. Thus, the question of how to prioritize systems thinking maturity models versus theory is a question of objectives: is the goal to make contributions to systems thinking knowledge, or contributions to successful systems projects? Academics and industrialists would answer this differently.

Despite assumptions that people who run organizational systems and people who study them might have similar interests [9], disjoints between academics and practitioners have long existed.[1]

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[1] For instance, most organizations do not employ theoretically sound management practices even though mounting evidence shows that certain empirically tested business practices are related to greater employee performance, productivity, and overall financial performance for the entire company [9,10].

"The gap is not restricted to the organizational sciences, but rather it is found in nearly all fields in which there are both researchers and practitioners" [8] (p. 340). There are reasons for this. Among them, systems scholar Ian Mitroff has observed that academics and practitioners differ in the types of information they believe constitute valid bases for action [11]. Such difference notwithstanding, the efforts of those interested in research and applied practice have been shown to benefit both [9,10]. Studies have shown that both quality and rate of knowledge creation are enhanced when tensions are present between differing stakeholders, disciplines, hypotheses, theories, prototypes, and implementation strategies [12–16]. This would suggest that two parallel streams of focus—pragmatic maturity model development, and scholarly development of theory about systems thinking maturity—would both be valuable; each would be incomplete without the other, and each would be strengthened by continued improvements in the other.

Thus, given the prospect of gains for both theory and practice, maturity models have emerged in many disciplines: psychology, business processes, project management, and knowledge management among them. In each case, the models have enabled comparisons among people and have had the effect of normalizing specific skills and behaviours deemed important to effectiveness [17]. As such, maturity models are having increased significance in aiding those interested in pursuing performance excellence in many realms of human endeavour [18]. Were systems communities to embark on the task of developing a means of assessing systems thinking maturity, we would be closer to clarifying what comprises systems competence across the widely varying subspecialties of systems theory and practice. Identifying unified, disciplined ways of representing systems thinking competence would go far to promote understanding and cohesion among these varied schools of systems thought. Likewise, it could contribute to the communities' ability to promote the value of systems knowledge in society and improve the effectiveness of cross-disciplinary dialogue that systems communities could have with other scientific disciplines.

The purpose of this paper is not an exhaustive survey of existing maturity models. Rather, it will discuss construct definitions, types of maturity models, critiques, and design considerations with an eye to examining how maturity models could be useful evaluation tools for systems thinking proponents to consider.

2. Maturity Models: Fundamentals

Maturity models are premised on the idea that successful performance is the result of effectively used knowledge. As such, models are tools for practitioners striving for excellence, groups interested in promoting collective expertise, and for scholars working to build developmental theories [19,20]. However, when applied to systems thinking, an immediate problem presents itself: what *is* systems thinking actually? A ubiquitous term [21], in the past 50 years many scholars have posited many definitions, e.g., [22–25]. Additionally, a sizable popular literature has emerged to teach people what it is and how to do it [26]. A central feature of systems thinking articles and books, in most cases, is the claim that becoming a skilled systems thinker rests on understanding what a system is and why systems tend to operate as they do.

According to social psychology, a fundamental first step in any epistemic is a knowledge domain [27]. In many fields, such a requirement is institutionally recognized: to be an accountant, one must have accounting knowledge; to be an historian, one must study history; to be an engineer, one must know one of several core disciplines; etc. [28]. It follows that the same logic would apply to an epistemic of systems thinking. However, regarding systems thinking, Checkland has been dismissive about anything that might be considered a knowledge domain:

> This is about the limit of what we can say about every example of systems thinking … there will be an observer who gives an account of the world, or part of it, in systems terms; his purpose in so doing; his definition of his system or systems; the principle which makes them coherent entities; the means and mechanism by which they tend to maintain their integrity; their boundaries, inputs, outputs, and components; their structure … [24] (p. 102).

Despite this pessimistic tone, a case can be made that a knowledge domain about systems themselves does exist.

For example, the literature pertaining to sociotechnical systems (e.g., [29] and elsewhere) is consistent in describing fundamental tenets such as these:

> People exist in relationship [21] and "systems … are intrinsically concerned with relationships" [24] (p. A24). Anyone attempting a systemic view must attend to "detail complexity" (i.e., the number and individual characteristics of a system's members [30]). Also important are the number and qualities of relationships that a system contains.
>
> Members of systems require one another to achieve their goals. They are connected in relationships of interdependence [31,32]. The strength of interdependence (or "interconnection" [33]) among members varies, affecting the degree to which a system can be viewed as cohesive.
>
> Human systems are purposive [24]. Such purposes arise from the ways members organize meanings [25]. A system's behaviour expresses explicitly espoused purposes [34] and also tacit purposes which may be unrecognized by members themselves [35,36].
>
> The manner in which systems are organized (intentionally or otherwise) arises from interactions among the system's members [23,37]. While such interactions tend to be patterned, they are also dynamic [21,38]. Hence, emergence is a feature of human systems [39].
>
> Sociotechnical systems contain dichotomies and tensions [26]. Working effectively with these requires, for example, that one consider both a system's parts [25,38] and its nature as a coherent whole [24,36,39], akin to working with both "figure and ground", as described by Gestalt principles of perception [40].

Though not exhaustive of the principles elucidated in systems books and articles, these tenets illustrate central ideas in the systems knowledge domain. Still, how can we know when a person is relating to such knowledge maturely or not?

Designers of maturity model tools imply that the way one uses knowledge reflects one's location on a scale of immaturity-to-maturity.[2] Popular encyclopedias such as Wikipedia convey that maturity involves:

- The ability to appropriately respond to the environment;
- Demonstrated capacity for effective decision making, suitable to context;
- The attainment of sophistication in the flexible use of knowledge and performance of behaviours;
- Appropriate levels of self-reliance and autonomy (in contrast to dependence on the oversight of authority figures);
- The ability to consider options and seek relevant advice, when appropriate; and
- The ability to exercise appropriate temperance and discipline, taking calculated risks without undue impulsivity.

People exhibit these abilities to varying degrees (that is, at various levels of maturity). The means by which maturity is demonstrated is *competence*, a concept of increasing interest since a seminal publication in the educational testing literature in the 1970s [43]. Since then, it has become a construct of increasing interest in theories of organizational behaviour, popularized by Boyatzis [44] and other

[2] Despite connotations that immaturity involves undesirable deficits (e.g., [7]), it is worth noting that psychologists have proposed that the stage of immaturity is an important time of experimentation [41,42] that is valuable to the development of individuals (and the evolution of a field's theoretical understanding of a developmental phenomenon [41]).

scholars. A comprehensive review of competence is beyond the scope of this paper, but for our purposes, in the realm of maturity models, competence at systems thinking would encompass a collection of traits, motives, self-image, and perceptions of social norms and behaviour enabling a person or group to direct systems knowledge in such a way that desired results are consistently achieved [6,45].

"Desirability" of the results achieved is readily measured in organizational settings. For example, in education, a curriculum gets delivered that is shown to enable students to meet intended learning objectives; in systems engineering, a complex structure is delivered that is designed to function effectively across its life cycle; in artificial intelligence, machines are created to accurately mimic human cognition. In any of these cases, success is measured in how well a team identifies and solves necessary problems in such a way that they develop and execute projects that meet sponsors' intended goals and success criteria [29,38,46].

However, binary thinking (e.g., desirable results vs. undesirable results, maturity vs. immaturity) could readily lead us to view systems thinking as something one can do or cannot. Writers have argued to the contrary, that systems thinking can be developed [21,29]. The maturity model literature takes pains to state that the use of specific knowledge is deemed important both in the capacity to both operate in a competent manner [6] and to improve that capacity: "Improvement ... require[s] some guidance on what to improve, and in identifying improvement efforts that will provide the most value ... Conducting assessments provides guidance in terms of current capabilities and identification of performance gaps, helping to identify where improvement is possible, necessary, or desirable" [47]. As we can speak of improving the capacity to deliver desirable results, so too does the maturity model literature speak of improving maturity. It does this by conceptualizing maturity in terms of gradations.

A central assumption of maturity models is that development of mature performance occurs in predictable patterns. This assumption is evident throughout scholarly papers in many disciplines that address maturity, for example:

- In motivational theory: e.g., that human drives are *arranged from basic to ultimate* [48];
- In management theory: e.g., that firms develop in stages along logical, predictable paths [49];
- In agile software development: e.g., that practices *evolve from ad hoc to continuous improvement* [50].

Proponents of maturity models believe that maturity is comprised of "tightly defined, repeatable, and predictable processes [that] directly contribute" to capable behaviour [51] (p. 147). The sense-making patterns underlying capable behaviour with respect to systems is largely unknown at this time. If they were understood, then models could be built to diagnose the maturity of a person's (or organization's) current systems thinking practices (i.e., the stage at which practice has stabilized [52]), in order to understand that person's (or organization's) current standing relative to others who are competent in systems thinking [5,53].

Maturity models are guided by the assumption that specifically interlinked collections of competently used knowledge and skills [52] comprise coherent *levels* or *stages* of maturity. Levels are ordered, thereby creating a hierarchical concept system that enables comparative ranking of different persons (or groups) and models a process of evolution by which a person (or group) can move toward increasingly sophisticated and reliable performance [17,54]. Different maturity stages are understood to be appropriate for achieving tasks of varying levels of complexity, giving rise to the notion of competence *fit*, which is another facet of maturity models. Rather than assuming that the highest possible level of maturity is inherently necessary, adherents of maturity models generally agree that maturity level should be matched to the difficulty of the task at hand, problems to be solved, and environmental context in which one is operating. At present, there are no consensually agreed-upon levels of sense-making based on systems thinking skills that could inform the assignment of systems thinkers to systemically complex projects.

If it is true that developmental behaviours are predictable, then maturity models are diagnostic, anticipating the likelihood of success a systems thinker would have when faced with a systems problem and given that thinker's current maturity level. Maturity models also claim to be prognostic, taking the idea of developmental predictability to mean that likelihood of success can be reliably increased by identifying areas of improvement that will progress one toward excellence. They do this by identifying areas of consensually defined weakness (or "fragility" [20]) that hinder optimal functioning [52]. As such, maturity models could facilitate planning, guidance, and control over future systems thinking performance by outlining what sense-making approaches in systems thinkers should be reinforced and prescribing the sense-making approaches of more mature stages as areas for prioritized development. "Organizations regularly invest in capability development; the capability maturity model aims to provide valuable guidance" in targeting training investment [20] (p. 146), in such a way as to strategically exploit existing capabilities and to strengthen potential ones [55]. Description and prescription lie at the heart of the maturity model's purpose and promise.

As indicated above, Checkland's claim was that every example of systems thinking is merely a matter of an observer with a purpose who defines a system and identifies the mechanisms that make its structure coherent [24] (p. 102). This view obscures the fact that observers differ in their capacities to define a system, identify its mechanisms, and understand its structural cohesion. Systems thinkers vary widely in their knowledge and skill, as do professionals of every sort. Accordingly, diverse parties have embarked on maturity model initiatives.

3. Varieties of Maturity Model

A variety of groups have made claims to understanding systems thinking maturity and codifying it. For example:

- In the United States, Carnegie Mellon University developed a model for the Hewlett-Packard Consulting company. Sabre Airlines has developed an in-house maturity model [56], as has NASA [57,58]. MITRE formulated a competency model reflecting its particular branded approach to government-funded research and development [59].
- Maturity models have been built based on analyses of human and business processes in European corporations such as Nokia in Finland and British Telecom in the United Kingdom [53].
- INCOSE UK has constructed a systems engineering competency framework to guide individuals and teams working in enterprises represented by its advisory board [60].

In each instance, maturity was defined in terms of a particular application or domain of human activity, ranging from innovation-generating situations like project management, the collaborative development of new computer software, and the ability to leverage Big Data [51,52,61], to routine organizational operations where effectiveness-enhancing actions such as practices of reflection are said to signify and enhance an organization's functioning [52]. Oriented toward different fields of human endeavour, what all of these maturity models have in common is the intent of formalizing and institutionalizing particular knowledges, skills, behaviours, values, and practices that are considered necessary for effective (i.e., mature) modes of operating in a particular context. The knowledge, skills, behaviours, values, and practices demanded in different fields of systems theory and practice are vast. However, the different contexts of human activity of interest to maturity modelers give rise to a variety of common characteristics in their models.

All maturity models aim to provide users with conceptual schemas for understanding how maturity is multifaceted in nature. Language used in models includes:

- "pillar factors", "dimensions", and "axes" [17];
- "structural components", "phases", "key agents", and "externalities" [54];
- "drivers" [50];
- "input competencies" [6]; and
- "tools" [53].

Models vary in the granularity with which they conceptualize these elements and their varied permutations. The degree to which models claim to be "tools" seems related to whether or not they portray maturity as a state resulting from tangible factors conducive to *quantitative measurement* by Likert scales or intangible factors better suited to *qualitative description* (the latter ranging from models using broad-based qualitative descriptions to those utilizing detailed descriptions that management theorists would characterize as "thick" or "rich" [62]. The ambition of some maturity models is to elucidate different modes of behaviour with respect to maturity, each useful in their own right. For example, models like these would describe clustered themes of systemic sense-making and the resulting behaviours. Such models would enable users to conceptualize qualitatively different ways that systems thinkers can function (not better or worse; merely different).

In contrast to maturity models that focus on qualities, the ambition of other models is to rank quantity—to rate different modes of functioning in terms of greater or lesser desirability. Such models seek to identify "poor" systems thinking in contrast to "good" systems thinking. Gradations are a feature common to these maturity models: they identify a range of human capabilities and behaviours and locate each in terms of its proximity to what designers understand as a state of ideal systems thinking maturity, thus creating a representation of distance and nearness to that state. Aspirational models like these vary in complicatedness, typically involving four or more levels (depending on whether or not stage zero is accorded any merit [17]), with each model including distinct components, dimensions, behaviours, or capabilities ranging from a few to upwards of 75 [20]. Such models are said to describe an ordered arrangement of levels, each understood as prerequisite to the next step along a singular evolutionary pathway oriented toward optimal performance (i.e., matureness) [18]. Users of these models can identify their location along the path via rating keys, or in some cases, exemplar situations given to represent how behaviour at each stage should look.

Developmentally oriented maturity models have an explicitly forward-moving telos, clarifying the meanings of desirable states such as *superiority*, *mastery*, and *excellence*. Where forward-moving progress is the aim, maturity models vary in the degree to which they explicitly assist users in advancing their path. Some models focus on within-stage characteristics, clarifying in sometimes great detail each level; they facilitate progress only indirectly, by merely naming the subsequent stage to be achieved ("benchmarking models" are examples of this [53]). Developmentally oriented models take a more active and direct role in facilitating users' progress, describing constraining forces that account for limited functioning (i.e., explaining why one is at a current level of maturity and not a higher one), and by naming drivers or enabling factors that would facilitate movement toward each next stage [50].

While all maturity models describe different stages of maturity, considerably fewer make claims to have uncovered the mechanisms of movement necessary to ascend between stages. That is, models differ in the claims they make to be *descriptive* of different states of maturity, *comparative* of modes of maturity exhibited by different people, or *prescriptive* of what actions to take in order to better one's level of maturity [54]. Thus, maturity models present themselves for two distinctly different purposes of use: (1) understanding how one operates, and (2) directing how to change that in favour of different or more useful ways of operating.

A final variance in existing maturity models is worth emphasizing. Few models portray maturity as context-free. Indeed, maturity itself should be defined in terms of one's skillful engagement with contextual factors. Most maturity models identify contextual factors that are pertinent to users and provide descriptions of how effective engagement with those factors typically looks at each level of maturity [47]. Maturity models in different disciplines vary in the attention they draw to environmental factors as central to the development and display of maturity. Systems thinkers work in wide-ranging settings. Amidst other factors, systems thinkers deal with myriad customers, audiences, organizational cultures, and leadership dynamics [51]. All are exigencies that demand a systems thinker's engagement if one were to perform at effective levels of maturity.

4. Criticisms

Fundamental to maturity models' raison d'être is the claim that adoption of a maturity model will translate into actual value for individuals or organizations. It is not clear the degree to which these models deliver on that promise [47].

For a maturity model to claim efficacy, there must be comprehensible underlying theoretical constructs and mechanisms of action. Central to the matter is the assertion that concepts called *best practices* do exist, and that the assumptions and conditions necessary to attain them are clearly understood. Saying that *maturity* is the state necessary for this attainment is insufficient; models claiming to address maturity should present a well-developed characterization of the construct. Unfortunately, "the central term of maturity is seldom defined explicitly", despite the number of entrants into the field of maturity models [54] (p. 338). It is unsurprising then, that questions have been raised about how accurately maturity is being codified [47], how effectively it can be measured [50], and whether the claims of its existence in hierarchical structures are a representation of reality that is accurate [20]. Maturity is a complex phenomenon involving many intricately related factors. As systems science has demonstrated, interaction among factors is central to understanding complex phenomena. Theorists and developers of maturity models have been criticized for having inadequately considered such interactions in developing the maturity construct and developing models that claim to account for it [20]. To *best practices* and *maturity* itself, we can add notions of *transformation* to the list of undertheorized aspects of maturity models. The allure of these models is the idea that they help a person or organization achieve ever-greater levels of maturity. Models vary in characterizing this transformation as *change*, *development*, or *evolution*. However, the mechanisms of action driving such transformations toward maturity are little understood. From psychology, for example, "[o]bserved relations between stages of moral development and various forms of social conduct do not establish that the structures of moral reasoning that define stages of moral development exert a significant causal impact on moral behaviour" [63] (p. 672). In the field of business process management, dynamics that generate movement among stages seem even less well understood: "All models implicitly expect organizations to eventually reach the top of the maturity ladder" [54] (p. 339), reflecting little understanding of the processes by which this destination is to be reached. Where mechanisms of action that drive the maturation process are described, maturity modelers argue that these, and not others, are to be followed. This has the effect of devaluing alternative approaches and rendering the modes of thinking used by all but a certain (i.e., "mature") segment of people "deviant and atypical, rather than reasonable and relevant" [47] (p. 172).[3] Enthusiasm for the idea of maturity models notwithstanding, a slipshod approach to building a solid theoretical infrastructure has left such models open to justified criticism.

Maturity models are particularly vulnerable in this respect: the literature generally agrees that maturity models do a good job of describing various degrees of maturity, but where models claim prescriptive insight, they often fail to meet users' expectations. We see this disappointment in users' claims that maturity models are oversimplifications of the lived complexities that users experience [53]—surely a concern of systems thinkers—presenting optimistic messages that maturity is a state eventually reached, yet vague on the details of how this actually occurs [67]. Where such details are forthcoming, maturity models attract criticism that the attention they do give to movement between maturity stages is vague or prescribes "step-by-step recipes" [54] that often do not work. Conversely, some models are so complex that they likewise fail to provide the promised rewards [20]. Too simple or too complex, if maturity models are to achieve fitness of use, the complexity of the frameworks they offer must reflect the needs of users. Likewise, the prescriptions they offer must fit the resources available to individuals or organizations. When models are too costly to adopt relative to the rewards

[3] For example, theorists have discussed such concerns in the project management discipline's critique of its own attempts to codify best practice and the means by which it is to be attained (e.g., [64–66]).

they claim to offer, no one wins. When they rigidify the maturity pathways they espouse, individuals or organizations whose problems and environments differ from those envisioned by model designers are left to try force fitting their way to maturity, usually unsuccessfully, or to customize models in ad hoc ways that may also fail [20]. Describing levels of maturity is relatively easy. Recommending pragmatic pathways by which it is to be developed demands attention to real-world impediments to mature behaviour, the difficulties involved in overcoming such impediments, and the need for feasible, flexible guidance that works.

"What works" is, of course, a matter of evidentiary support, and here is where the most damning critiques of maturity models arise. The increasing numbers of maturity models suggest interest in authoritative insight and expertise on how people in varying jobs can operate more maturely; this enthusiasm has, however, been unmatched by actual scientific study to validate such claims. Despite the intuitive appeal of maturity models and anecdotal confirmation that they are useful, research that studies their rigor, validity, or usefulness in correlating model prescriptions with actual success is scarce [45]. When enthusiasm outweighs empirical evidence, the value of a particular model, and maturity models in general, is called into question.

The criticisms that maturity models face are fundamental and appropriate. If such models are to achieve what they set out to achieve, academic communities must undertake serious reflection about the characteristics of maturation to replace the vague belief that it is associated with development in a good direction. (For this reason, scholars in fields such as information science have called for the development of research standards for model designers [53].) Despite the warranted misgivings, there are models that are believed to be relevant and worthwhile: "Certain maturity and competency models might be robust enough to become the global standard for certification purposes" [6] (p. 11). This possibility, that maturity models can stand as international standards of how effective functioning can be measured and developed, has inspired this brief overview.

5. Design Considerations for a Maturity Model of Systems Thinking Competence (MMSTC)

As discussed earlier, knowledge about systems is foundational to systems thinking. Broadly speaking, knowledge generally tends to be associated with thinking. However, it has been argued that a person can know facts about systems without being a systems thinker [26]. This argument is consistent with Kruglanski's epistemic theory, which recognizes that possessing a knowledge domain is necessary, yet insufficient [27]. Another key element of epistemics is the particular modes of thinking that are conducive to perceiving something accurately. This he calls "welcoming cognitive conditions"—the mental skills and cognitive stances that one requires to focus one's understanding in order to apprehend a thing. Here, we would say that being a systems thinker requires knowing facts and also utilizing particular ways of perceiving those facts [37]. Coming to know systems facts is a task readily handled by universities; institutions training one on how to do systems thinking are lacking [68].

This is not to say that all existing maturity models for systems thinking have overemphasized knowledge and neglected cognition. The engineering field has several exemplars of models that include cognitive skills, e.g., [33,38,58] and others. However, fields of systems thinking beyond systems engineering are largely deficient in articulating what we might term welcoming cognitive conditions for systems thinking. A Maturity Model for Systems Thinking Competence beyond engineering, then, would incorporate key elements of the domain of general systems knowledge as it is presently understood. For any model to be considered worthwhile, it should also include cognitive orientations deemed necessary for systems thinkers in any discipline to perform systems thinking in competent ways. The facility and sophistication with which one uses them would be indicative of one's level of systems thinking maturity, and without such orientations, it is questionable whether one could be said to be using systems thinking at all. What might be welcoming cognitive conditions necessary for systems thinking? The following could be considered:

An orientation toward causality: A system's structure is made up of causally linked variables [31]. A focus of systems thinking is identifying both those variables and the nature of the causal relations among them. To Checkland, focusing one's attention on simple cause and effect sequences is an inferior form of thinking [24], or at least, not one to be understood as *systems* thinking. Rather, the degree to which systems thinkers succeed in orienting themselves to multiplicities of causal relationships suggests the degree to which a system's complexity will be appropriately understood.

An orientation toward logic: Systems thinkers regularly face phenomena that do not make sense, or rather, the sense underlying a system's behaviour is not always readily apparent. The logic of a system—the "set of principles underlying the arrangement of elements" (Oxford Dictionary)—is what must be grasped if one is to understand the way a particular system coheres, what makes it robust, and how it maintains its equilibrium [24,31]. In the face of complexity, people tend to oversimplify why a system is behaving as it is or to dismiss it as illogical [36]. Neither cognitive strategy supports the ability to accurately discern the logic underlying a particular system's behaviour.

An orientation toward explicit and implicit structures: Systems can appear explicit, comprised of obvious rules giving rise to understandable behaviours. The awareness that structure generates behaviour [30] enables a systems thinker to avoid attribution errors common among people who do not understand systems (for example, assuming that a particular person's motivation or actions has caused a system's "problem"). Knowing that behaviour is expressive of structure, a systems thinker wanting to change counterproductive behaviour will imagine potential changes to structural design, rather than assuming that a simple substitution of "problematic" elements for others will overcome the confluence of implicit structural factors delimiting how those elements will likely behave [69,70].

An orientation toward subjectivity: Subjectivities are particularly potent features of human systems [71]. Each person possesses mental models of reality that, taken together, create and sustain a system's identity [70] and the degree to which that system is able to learn and change. Mental models eliminate feelings of ambiguity and influence how a system's members think and act; "unless you understand them, you will not understand the system" [70] (p. 147). Yet, inherently, mental models are an aspect of human subjectivity not available for direct measurement [72]. Thus, systems thinkers must orient themselves toward the difficult work of eliciting communication about mental models,[4] translating people's tacit perceptions into discussable language [31,73]. While doing this, they must also refrain from imposing their own judgments on the models of others [25]—striving for a "rigorous approach to the subjective" [24] (p. A43).

An orientation toward self-reflection: In systems thinking, understanding the mental models of members of a system—from *their* perspective—is necessary [70], and necessarily difficult. Always, it must be acknowledged that human subjectivity—others' and our own—is incomplete. While subjectivity enables us to function in reality, it does not provide a full or fully accurate representation of a system in which we are operating. Systems thinkers themselves hold incomplete (and thus inaccurate) understandings of a system. They, no less than anyone, hold preconceived values, "taken as given" assumptions, and their own personalized logics [24,31], all of which can obstruct understanding and clear communication.

[4] A variety of techniques have been used to help elicit mental models so that they can be more openly communicated and understood. These range from the use of diagrammatic techniques akin to fuzzy cognitive mapping and systems dynamics approaches, to rich pictures and other participatory modeling approaches that both surface differences and enable consensus analysis [72].

> As such, systems thinkers must orient themselves outwardly toward the systems they seek to understand and also inwardly toward themselves [26]. Discomfort is an inherent part of such dual orientation; oppositional emotions (i.e., disbelief, disagreement, etc.) that emerge in systems thinkers are reliable signals that their personal subjectivities are being challenged [69] and must be consciously reflected upon [24] so that they can be usefully discussed with others.

These orientations toward causality, logic, explicit/implicit structures, subjectivity, and self-reflection could be considered mental stances without which systems thinking is not possible. With verification (to be discussed below), these orientations and/or others could come to be understood as welcoming cognitive conditions uniquely important to systems thinkers and as standards without which a Maturity Model for Systems Thinking Competence would be insufficient.

Were a Maturity Model of Systems Thinking Competence to be developed that would be relevant and worthwhile to systems thinkers in various professions worldwide, systems research communities would do well to glean lessons from modelers and theorists from other disciplines. I turn my attention now to highlighting key considerations to be addressed in any future initiatives to develop competence models for systems thinkers.

Consistent with the move underway to codify the nascent science of systemology [1,2], this author agrees with arguments against maturity models that rely solely on anecdotal assertions (including the welcoming cognitive conditions synthesized above). As Edson and Metcalf [74] have written, good systems research responds to the need to marry scientific discernment with lived experience. Any research initiative to establish a model of systems research competence must consider this. Models that describe levels of maturity solely based on anecdote will fail to meet the rigours of good science and will run the risk of misleading systems thinking practitioners who trust them. There is irony in the fact that most maturity models claim that one cannot skip steps on the path to mature standards of competency, while modelers in most disciplines have skipped the crucial step of empirically validating their own models. Without such validation, claims that experts understand the nature of systems thinking maturity, and that systems communities should measure themselves by those claims, tread on shaky ground. Thus, the development of a maturity model with an explicit theoretical base is vital.

A Maturity Model of Systems Thinking Competence should define constructs like *maturity* and *maturation* and must identify observable indicators of maturity levels and the characteristics of paths that lay between them [54]. Numerous bodies of theory could provide useful guidance in the development of a systems thinking maturity model:

- theories of human development in cognitive psychology can inform a theory of the maturation of systems thinking competence;
- educational theories can inform understanding of systems thinking skills improvement;
- convergence and divergence theories can help explain path dependencies among systems thinking maturity levels.
- theories of bounded rationality and information symmetry can inform understanding of how actors at varying levels of maturity make decisions and exert agency in both ineffective (i.e., immature) and effective (i.e., maturity-building) ways [18].

Much discussion about maturity could lead to the implicit assumption that maturity models focus on the maturity of *individuals*. While many do, it is also the case that some models focus on the maturity of *organizations* with respect to their competency in business processes, project management, agile software development, etc. It may be possible to create maturity models for individual systems thinkers, working in education, management, or the social sciences, for example. It may also be useful to create maturity models for teams, for example, working in fields such as artificial intelligence. Were there an initiative to develop a broadly applicable maturity model of *collective* competency in systems thinking, organizational theories can be useful in developing models for organizations in which systems thinking takes place [53]:

- the resource-based view of the firm [4] has been mentioned earlier as useful for conceptualizing knowledge and skills as organizational assets;
- organizational change theories [49] provide understandings about how change initiatives can be regulated as well as expectable conflicts, drivers, and impediments; and
- life cycle theories and teleological theories of goal formation and implementation [75] can be useful in theorizing the development of organizational capabilities.

Systems thinking communities have at their disposal numerous theory candidates that can assist in the development of sound maturity models for both individuals and groups.

Building on a solid theoretical base, all the strategies and methods demanded of good systems research should be applied to any initiative to develop a Maturity Model of Systems Thinking Competence. Model development must include particular care to rigorously differentiate relationships of inference and causality [45] that anticipate the criticisms leveled at maturity models in other fields, whose claims about what actions can reliably move one to greater maturity rely on scant evidence or none at all.

In any scientific endeavour, care must be taken to avoid generalizing findings from one instance to all conceivable contexts. Röglinger, Pöppelbuß, and Becker have noted that maturity models often do not translate well in all situational contexts their users face [54]. Maturity models have struggled to account for the idiosyncrasies of the problem spaces in which users work. Differences in the size of projects, technical complexity, and organizational culture greatly affect the work people do and the ways they do or do not develop maturity [6]. In particular, work that demands unique processes are hard for maturity modelers to predict and take into account. This makes it difficult to imagine the kinds of skills and behaviours to be called forth from users, which makes it difficult to legitimize certain skills and behaviours as exemplars of maturity [51]. While it is problematic to overstate the number of settings to which a maturity model should apply, so too is it problematic to prescribe qualities—in the name of maturity—that implicitly privilege a too-narrow number of people based on moral typologies [76], gender roles [77], reputations of being proven stellar in particular environments [21], or preference toward particular schools of systems work (e.g., systems dynamics, systems modeling, etc.) [38].

A case can be made that the discipline of systemology is uniquely well-placed to develop frameworks that *can* be generalized in rigorously defensible ways. As Midgley [78] and others have written, a strength of the systems field is the way it encompasses a very diverse collection of perspectives, priorities, and tools. However, since the caution against overgeneralizing applies also to systems science endeavours (W. Varey, personal communication), one might conclude that any initiative to develop maturity measures for systems thinkers would require different models for every one of the widely differing systems approaches. Recently, however, Hammond [79] reminded us about the origins of the modern systems movement that was motivated by the desire to identify patterns common across the boundaries that typically divide academic inquiry. (A central text in the field does, after all, characterize the movement as a quest for a *general* systems theory [22], and organizations like the International Society for the Systems Sciences have been established "to foster the investigation of the analogy or isomorphy of concepts, laws, and models in various disciplines and professions" http://isss.org/world/administration/bylaws). Further, it has been argued that certain perceptual and behavioural competencies are common across multiple systems traditions and methodologies [80].

A credible case can be made that a unified Maturity Model of Systems Thinking Competency is possible. In its creation, designers should be aided by the contributions of systems theorists who have contributed to the field by calling for implicit biases to be surfaced and critiqued in systems work (e.g., [81,82]). For a Maturity Model of Systems Thinking Competencies to be ethical and effective, such biases must be a focus of attention.

Other characteristics of good maturity models would serve systems practitioners well. User-friendly design is important. Systems thinkers operating in different cultures and problem domains should have assessment tools that are accessible and comprehensible. Model theorists have stressed the importance of well-structured and easily applicable self-assessment tools [54]. Some have advocated for tests that are "quick" [83]. Others have pointed out the usefulness of models that include templates and checklists for users to collect evidence and artifacts of competent activity at each level of maturity [17]. Should systems communities elect to computerize a maturity model, it should feature intuitive graphical interface and easy report-generating capabilities aligned with principles of good software design [17]. Should systems communities choose to go beyond a descriptive model to actual evidence-based recommendations on advancing one's level of systems competence, then "relevant drivers and best practices for a roadmap to [increasing] maturity" [50] (p. 141) in systems thinking should be provided in concrete, actionable language that is commensurate with a level of granularity suitable to each maturity level [54]. An emphasis on pragmatic tools, technology, and developmental plans for a Maturity Model of Systems Thinking Competence would have the effect of meeting systems practitioners in their lived experience, while providing transparency about the qualities and components believed to be indicative of competent skills and behaviours at each stage of systems thinking maturity [54].

It is worthwhile to remember critiques that maturity models imply that adherence to particular schemes of behaviour, uniform techniques, and particular decision-making strategies can automatize and guarantee sure progress toward maturity (e.g., [63]). This trivializes the situational complexities users face and would do systems practitioners ill service. It is axiomatic that systems workers grapple with systems that are messy—wicked, even [84,85]. The grappling would be no less for those attempting to develop a maturity model for competencies relevant to systems thinkers working in complex contexts. Competent systems thinking cannot be routinized; the nature of systems work defies this possibility. Mature systems thinkers are aware of the ways the systems they study are interdependent with the environment and aware of the ways in which they themselves are likewise interdependent [86].

The competing forces of unity and plurality that are central to systems work are mirrored in the structure of maturity development evident in existing models. Every model presents its maturity stages as comprised of multiple interacting factors. Those factors include knowledge, skills, and metacognitive abilities [52]; they involve the interplay of cognition, emotional development, moral development, and decision-making capacities able to resolve difficult psychosocial conflicts (Wikipedia.com—"Maturity"). In other words, any single stage of maturity operates as a system of interdependent elements. Maturity models are complex, involving dynamic interactions unfolding in ways that can shift a person into progressively more mature levels of functioning—i.e., the development of maturity is a phenomenon involving the emergence of successively higher orders of coherence in a person's capabilities.

"A static or prescriptive model of maturity cannot hope to provide the level of guidance that organizations require in making effective choices" [47] (p. 181). Similarly, "the development and refinement of a [theoretical] construct is an ongoing process that requires attention to clarifying the constructs' definition and parts" [87]. The work of developing a maturity model for competent systems thinking must be iterative. Research design for a maturity model project should be both rigorously planned and intentionally modified throughout the research life cycle [88], acknowledging that systems research is a circular process that builds upon previously obtained knowledge and responds to experience gained through the course of the study [89]. The project of developing a maturity model for systems thinkers ought to proceed as would any sound systems research initiative. Careful attention should be paid to problem structuring [89]. How the task is framed should be adjusted as the project unfolds and modelers reflect on what they are learning [90]. Central to the development of a Maturity Model for Systems Thinking Competence would be identification of success factors—for example, education, knowledge networks, use of systems tools and techniques, organizational climate, and the support of leaders are all factors identified as conducive or obstructive to maturity in other domains of knowledge work [5]. The relative contribution of these and other factors to systems thinking would need to be evaluated [6], enabling us to clarify the nature of maturity as it pertains to systems work.

6. Conclusions

If there is to be a more systems-literate world, people working in different roles must play a part. In each role, particular systems competencies must be brought to bear, and those competencies will vary in maturity within each person. Learning theory tells us that experience in doing something does not translate into maturation unless we reflect it against our existing understandings and assumptions [52]. Thousands of intelligent, committed systems thinkers have contributed their expertise to pressing world problems for decades now. Are those experiences maturing into increased competence in the practice of systems thinking worldwide? This is a matter for thoughtful consideration.

In several industries and academic disciplines, maturity models have been a way to address the question. A maturity model for competence in systems thinking would be a difficult undertaking. The number of situational contingencies and mediating factors one typically encounters in systems projects is considerable. Identifying the competencies that actually contribute to project success is not easy, as scholars working in other fields have discovered. Navigating the tension between a maturity model's formality and flexibility is a challenge [20]. Beyond these, engaging in critical self-reflection—which lies at the heart of maturity assessment—opens the possibility of unexpected and possibly uncomfortable discoveries about one's own immaturity [52]. A maturity model for competence in systems thinking would be a formidable task, but this is not to suggest it ought to be a task left undone.

The task ahead would need to begin by developing clarity about key concepts:

- What is immature (i.e., rudimentary) systems thinking?
- What does mature (i.e., advanced) systems thinking look like?
- What competencies contribute to maturity in the systems thinker?
- By what means could these competencies be measured?
- How do people translate systems knowledge into effective systems thinking skills and behaviours?
- In what ways do systems thinking competencies stabilize (i.e., what levels of systems thinking maturity could be said to exist)?
- How does one develop from one level of maturity to another?
- What are the relationships between competent use of systems knowledge, systemic sense-making skills, and successful project outcomes?

Even once we develop answers to fundamental questions such as these, the work of clarifying, refining, and enhancing a maturity model would be ongoing—cumulative work that scholars in many disciplines have struggled to do well [54]. Empirical studies to establish the validity and usefulness of the model would be necessary, particularly with regard to its ability to predict and guide ways of increasing maturity to greater levels of effectiveness [45]. If a Maturity Model for Systems Thinking Competence is to be worthwhile, its accuracy and applicability must gain widespread acceptance among the systems sciences scholarly communities and systems practitioners alike.

In all this work, the underlying premises for creating a maturity model for systems thinking must be clarified and kept at the forefront. Those premises are yet to be determined. However, some broad-based possibilities can be mentioned here. People who participate in international systems organizations share a vested interest in contributing to more accurate understanding and effective solutions to systemically complex problems. Systems thinking, we believe, is central to that aspiration. Systems thinking involves unique, or at least uniquely combined, human competencies. The competence people exhibit in doing systems thinking varies in maturity. Competence in systems thinking is a developmental process and can progress beyond ad hoc approaches typical of new systems thinkers. The academic disciplines of systems science, and the constituents they serve, would be better served if the discipline could clarify the competencies and skills universally necessary to doing good systems work. This would legitimize systems thinking competence and differentiate systems thinkers from those using other kinds of thinking, which would enable recognition of the unique contributions that systems thinking makes. In a variety of settings, the approaches, intelligences, knowledge domains, and welcoming cognitive conditions associated with systems thinking would come to be better recognized and valued. Maturity Models for Systems Thinking Competence could accomplish important things: development of systemology, increase in the value that systems theory and practice can deliver to pressing world problems, and strengthening the legitimacy of systems knowledge as a branch of science of equal merit to other established disciplines.

A Model of Systems Thinking Competence could contribute to our understanding of the different kinds of systems thinking work that people do. Generating such a model would engage members of systems communities in dialogue about the sociocultural and political realities that impact effective systems work. The unanalyzed processes of "adaptation and negotiation within organizations" that impact systems thinking would be surfaced [52] (p. 19). The ways in which competent systems thinkers secure budgetary support, the way their work gets evaluated, and the way they generate lessons for the future would be important in assessing the factors that contribute to the development of systems thinking competence. The ways in which systems thinkers' intellectual capital is or is not transferred to others within organizations and industries would need to be addressed [5]; the impact of mentor relationships on the maturation of systems thinkers' competence could be investigated. A systematic process of collective reflection about factors such as these would clarify important situational contingencies that mediate the development of maturity in systems thinkers.

A Maturity Model of Systems Thinking Competence would make transparent the assumptions underpinning current understandings about what constitutes effective behaviour in meeting the challenges of complex systems. It would facilitate the scientific imperative of enabling assumptions underlying a maturity model to be intersubjectively verified by scientists and practitioners. It would mobilize the sharing of interpretations about the sense-making and problem solving practices that systems communities espouse. Greater understanding about the work we do as systems thinkers will not be gained in social isolation. A Maturity Model for Systems Thinking Competence would become a shared analytical lens through which we could understand and judge the competent use of systems science knowledge, skills, and behaviours. It would, thereby, act as a force for community identity building, with the potential to substantially affect the impact that systems thinkers can make in the future.

Acknowledgments: The author wishes to thanks Kajal Akruwala, MBA, for her assistance in this research.

Conflicts of Interest: The author declares no conflict of interest.

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Natural Systems Thinking and the Human Family

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Received: 2 April 2018; Accepted: 30 May 2018; Published: 1 June 2018

Abstract: Broadly speaking, natural systems thinking is defined as a way of thinking that endeavors to conceptualize the functioning of living organisms as dependent on predictable forces at work within and around them. Systems concepts help to bring the function of those variables and life forces into better view. Psychiatrist Murray Bowen over the course of several years and a major research project at the National Institute of Mental Health (NIMH) developed a theory of the family as a system. He considered his theory a natural systems theory, "... designed to fit precisely with the principles of evolution and the human as an evolutionary being" The human family system, a network of relationships, linking each family member to every other, responds dynamically to its environment and the conditions to which all members must adapt. Each family member's behavior influences that of every other to some degree. Although ideas of a general system theory and cybernetics were developing at the same time, Bowen reported that he knew nothing about those ideas at the time he developed his thinking. He believed that his systems orientation derived from his study of systems in nature and not from the "systems thinking" of the period. An emerging systems paradigm in biology and evolutionary thinking focuses on collective behavior and appears consistent in principle with Bowen's thinking about the family. The collective behavior of the family unit cannot be understood by looking at the characteristics of the individuals who comprise it. The human family presents a highly integrated, interactive system of adaptation. Its roots extend along the path of hominid evolution and share common elements with other evolved collectivities. The complex development of the human brain appears to have co-evolved with the interactional processes of the family. The Bowen theory provides the potential for an integrative theory of human behavior reaching beyond the focus on the physiology and psychology of the individual to the operation and influence of the family system. Such an integrative theory can offer broader explanatory and investigative pathways for understanding physical, emotional, and social problems as they emerge in human activity.

Keywords: family; family system; natural systems thinking; Murray Bowen; integrative theory

1. Introduction

Systems thinking represents an emerging paradigm in the life sciences. Rather than focus on the functioning of individual parts that make up a larger whole, systems thinking looks at the way in which the parts interact with one another to create the larger whole, and how the larger whole, in turn, regulates the parts which make it up. The back and forth interaction between the parts and the whole is observable and predictable in living systems. Systems thinking focuses on the facts of how the parts of a network interact and under what conditions the patterns of interaction change. Murray Bowen, a family psychiatrist and researcher, applied systems thinking to the human family when he observed, "The family is a system in that a change in one part of the system is followed by compensatory change in other parts of the system" [1] (pp. 154–155). Systems thinking in the natural sciences has the potential to lead to the formulation of natural systems theories that can predict the functioning of biological units under specified conditions, including the way the unit is influenced by the larger systems of which it is a part and also by its subsystems.

In this article, several examples of natural systems are described as a context for introducing the family as a natural system. We describe the co-regulation of the individual and the family system as conceptualized by Bowen in his theory of the family as an emotional system [1]. We propose a few ideas about the potential value of this view of the family as a natural system to contribute toward progress in science and in addressing human problems in a changing world.

2. Systems Thinking and Natural Systems

The study of all forms of life has inevitably led to the observation of interactive processes at play both within and between them. The conceptualization of such observations requires some form of systems thinking. As molecular biologist James Shapiro writes "The science of the 21st Century deals with the interactions between multiple components of complex systems, ranging from aggregates of elementary particles to the behavior of the largest structures in the cosmos [2] (p. 145)". The observation of interactive processes occurring from the level of the genome to ecosystems has led to a range of discoveries operating in complex living systems such as those cited below.

Such interactional processes act reciprocally. Two or more variables influence one another as they interact, mutually influencing and modulating each other. For example, at one time gene expression was viewed as a uni-directional process of DNA → RNA → proteins. It is now known that the genome interacts with and can be modified by the cellular and other environmental systems. Research over the past several decades has established that cells have proofreading and repair systems to correct errors when DNA replicates [2].

The emerging field of social genomics has discovered certain types of genes subject to social regulation [3]. Pathways between these socially sensitive genes and neural and endocrine systems influence adaptiveness. Parental care of offspring during the perinatal period can regulate the expression of genes that influence both parenting and the stress reactivity of the offspring across its lifetime. These effects continue for the next several generations [4,5]. In the human, individual genomes operate differently depending on the presence of other people and how they are perceived [6]. Threat and even the perception of threat can influence the expressions of genes related to health and illness. As a result, reciprocal interaction in a family can affect the expression of genes related to the health and illness of every family member.

For much of the twentieth century, the endocrine and immune systems were believed to function autonomously. The discovery that these systems express similar interactional neuropetide and hormonal mediators as well as receptors for these ligands and cytokines led to the further discovery that they represent a highly integrated and interactive system. Understanding the ways in which the nervous, endocrine, and immune systems communicate with one another has led to important new knowledge and new hypotheses about the pathways through which stress impacts adaptive behaviors involved in selfregulation [7,8]. Recognition of the mutual interaction of these major physiological regulatory systems has led to increased understanding of the complexity of such systems.

The study of ant behavior by Deborah Gordon led to the observation that the colonies represented complex adaptive systems that could not be explained by the behavior of the individual ants. It is the interactions among individuals which determine the functioning and morphology of the colony's members. She writes " . . . over the last 15 years, it has become clear that many biological systems are regulated by networks of interaction among the components, from genes to individuals. It is colonies, not individuals, that behave in a predictable way [9] (p.46)".

The examples cited above represent only a few of the many discoveries from the observation of interacting entities that had previously been viewed as separate but later determined to be co-regulating components of larger wholes.

3. Co-Evolution of the Brain and the Family

The shift from focusing on individual entities such as the gene to observing their functioning as interactive components in more complex systems led to the discovery of regulatory processes that could not be observed with a focus on the entities themselves. Observing the brain and the family as they evolved provides a basis for understanding the family as a natural system that regulates and is regulated by its individual members.

Natural systems thinking considers all living systems products of evolution that continuously adapt to their environment. The need of living systems to maintain a stable internal environment amidst adaptive change has resulted in increasingly complex regulatory systems to insure the integrated stability essential for survival. The evolution of nervous systems and the brain allowed the integration of more complex multicellular creatures into single organisms with an increased capacity to adapt to a wider range of environments. For most of human evolution the family has consisted of large extended families, multiple caretakers of infants, and a wide range of social interactions for the developing child. The rapid expansion of the neocortex in the hominid line during evolution may reflect the selective advantage it provided in adapting to the social complexity of life in large clans [10].

The co-evolution of the family and the brain, building on the maternal/offspring attachments of our mammalian ancestors, involved profound adaptations in the hominid biology [11]. The development of the human brain requires a prolonged period of dependency on parents and family members. The development of the neocortex occurs largely after birth. Doubling in size in the last half million years, the human brain evolved in the context of an evolving family interactional system. The human is the only great ape to exhibit cooperative breeding that involves an increase in the level of social tolerance, greater responsiveness to social signals, and the active parental care of infants by others in the larger group. It is posited that the cooperative care by fathers and other family members, i.e., grandparents, allowed for the prolonged period of development for offspring, as well as a more complex social environment requiring increased intelligence, such as theory of mind, for successful adaptation. As neuroscientist John Allman [12] writes: " ... the development of the brain to the level of complexity we enjoy—and that makes our lives so rich—depended on the establishment of the human family as a social and reproductive unit (p. 2)".

4. The Bowen Theory

From 1954 to 1959, psychiatrist Murray Bowen led a remarkable research project at the National Institute of Mental Health (NIMH) in Bethesda, Maryland. Entire families with a schizophrenic family member came to live in the Clinical Center for varying periods of time. The researchers observed the families around the clock and kept detailed notes of all interactions. Quickly the field of observation expanded to include the hospital staff as well in their engagements with various family members and with the family as a whole. In a sense Bowen conducted a field study of the human family, recording the ebb and flow of its processes from moment to moment.

4.1. The Family Emotional System

Bowen proceeded inductively, drawing upon his pool of observational data to formulate theoretical propositions. He quickly realized that the behavior of any given family member is linked to the behavior of other family members. The family behaves as a whole, a unit, analogous to an organism. Deep emotional connections link family members to one another. The emotional connection finds expression in sequences of interactional behavior (patterns) that emerge and recede in conjunction with levels of anxiety and stress in family members. For example, when one person moves toward dysfunction, another appears to increase his or her functioning in compensation. When one person becomes upset, another steps in to attempt to calm things down.

Bowen had discovered what he came to call the family emotional system (FES). Family members appear connected and co-regulated. Within the emotional system, family members display an exquisite sensitivity to one another. They exchange interdependent feeling states and reveal instinctive emotional reactiveness to one another. Interconnected cycles of emotional reactivity produce emerging and receding interactional sequences linked to stress and emotional tension in various relationships. As a part of the FES, family members participate in a perceptual framework held in common. The family psychological fusion includes sets of perceptions and interpretations of one another, of the external environment, and notions of what is to be feared and of how to respond when threatened. In the FES emotion provides motivational energy to family members that is expressed in relationship interactions.

4.2. The Balance of Individuality-Togetherness Forces in the Family

Bowen proposed that individuals in the family continuously respond to two powerful instincts or forces. The first is to be an emotionally autonomous individual, free from the constraints of relationships to pursue one's own goals and plans. The second is to be connected to others and a part of the group. He called these pressures the "togetherness-individuality forces" [1] (p. 277). Each individual attains a balance between these two forces for oneself. Each family also reflects a broader family balance of these forces. When disturbed, re-balancing or re-stabilizing mechanisms can be observed to come into play to support and restore the balance. These compensatory mechanisms can be likened to the allostatic mechanisms of the organism. They appear to redistribute quantities of anxiety and stress within the system.

The constant pressure on the family to adapt to changing conditions affects the togetherness-individuality balance. Bowen observed that as anxiety and stress increase, family members increase the pressure they put upon one another to remain connected, to see and respond to the challenge in the same way, and to put the family well-being ahead of one's own welfare. In the face of increased togetherness pressure, individuals react emotionally without careful thought. Some give up portions of their individuality in order to comply with the demand for connection and unity. Others may rebel. Yet others may withdraw silently. If prolonged, the family readjusts with a ratio of togetherness to individuality that becomes the new norm for the system.

4.3. Stress and the Level of Differentiation of Self

Bowen observed that individuals vary in their ability to function when stressed. Some are able to maintain careful thinking they use to guide behavior when pressured. They appear able to maintain their cognitive skills when stressed. Others appear to lose their ability to regulate themselves and rely automatically on instinct or emotion for direction. He proposed a theoretical scale of differentiation of self, placing individual variability in self-regulation and ability to maintain cognitive functioning when stressed on a continuum from those with the least to those with the most ability. The balance of individuality and togetherness reflects the level of differentiation of self. Higher levels of differentiation have a more equal balance between the two forces while lower levels are tilted more toward togetherness.

The level of differentiation of self reflects for any given person the integrated developmental trajectories of agency and autonomy, competency, and maturity. It finds expression in the person's development of principles used to guide behavior, in the ability to regulate behavior in the pursuit of goals, in his or her tolerance for and ability to manage anxiety, stress, and fear, and in the ability to maintain contact with important other people who may have different goals and objectives from his or her own.

The interplay of levels of stress and differentiation of self produce the dynamism observable in human families. Tension (a product of individual and interpersonal anxiety and stress) can best be understood as a load, drag, or strain upon the capability of the family system to maintain itself and adapt to changing conditions. As tension increases in a particular family, the family system responds with set patterns of individual and interactional behavior that appear and recede with stress conditions. These patterns appear to redistribute quantities of anxiety and stress within the system.

Vulnerable individuals take on or embody greater amounts of anxiety and stress than less susceptible family members. The more vulnerable family members become those most likely to develop a physical, emotional, or social symptom.

Anxiety and stress levels wax and wane both individually and in the family system. As they go up and down, tension levels rise and fall with them. As tension increases in the family system, behavioral patterns noted above emerge that appear to reflect the tension while simultaneously limiting its effects. Families appear to vary in the amount of tension chronically present in the family system. Some families have little, some a great deal. A chronically tense family faces current challenge with less reserve capacity to adapt.

4.4. Relationship Patterns in the Family Emotional System

4.4.1. Patterns Involving Two People

Conflict, distance, and a pattern Bowen described as an "over adequate-inadequate reciprocity" [1] (p. 27) wax and wane, generally within the marital pair in a nuclear family unit. For example, in a particular family system, one relationship (a marital pair, a parent-child duo, a sibling pair) appears to be most sensitive to rising tension. As the tension climbs, the sensitive relationship may display more interpersonal friction. Or they may withdraw from one another, avoiding and not speaking to one another. The patterns of conflict and distance may alternate in the pair. Periods of intense conflict may cycle recurrently with periods of withdrawal. The over adequate-inadequate pattern describes the interlinked behaviors of two people. One functions more competently for the dyad, while the other accepts the inadequate position in order to avoid the discomfort of interpersonal conflict. The more adequate appearing individual appears to gain emotional strength from the posture in contrast to the less adequate person who appears to yield strength.

4.4.2. Triangles

Multi-sided relationships beyond the dyadic take on repetitive patterns of a three-way interaction known as triangling. The dynamical repetitive nature of such recurring patterns serves to create a structure or order for family interaction that operates in a predictable fashion beneath the sometimes turbulent surface of family relationships. Triangling appears in a relationship network as tension develops between two individuals. When that tension exceeds the person's ability to maintain differentiation of self, he or she predictably moves to involve a third person. Within the family the third person chosen is one who has emotional significance to the tense twosome. For example, as tension mounts between siblings in a family, typically one of the siblings will move toward a parent with a complaint or story about the other child. The movement occurs with a communication to the third about the difficult other person or about the difficult relationship. The communication includes content (the story being conveyed) and emotion (a valence or charge the communicating individual injects into the communication). For example, the child attempting to involve the parent presents his or her tale with a whining, complaining voice tone, stressed countenance, and a quality of demand that the parent finds difficult to ignore.

With the involvement of the third, the anxiety and tension between the original two now can move among three relationships instead of the original single one. The initiator of the triangling move now has an ally in the parent, and the tension shifts to the relationship between the second child and the parent. The pattern can shift again, with the alliance reforming between siblings and the parent again placed in the outside position. It can shift yet again, leading to a closeness between the second child and the parent, leaving the original child who complained to the parent in the outside position. The triangle allows stress and tension to shift among the various relationships, fending off the stress-based impairment of any particular person. When tension decreases overall, the patterns of the triangle recede as if dormant, emerging again when tension inevitably increases.

Predictable movements occur within the triangle. When the tension between two is high, one of the two will attempt to attain the outside position and involve someone else in the tension position of the twosome. For example, when tension develops between a parent and a teenager, the teenager can complain to the other parent about the situation. This complaint can transfer the tension to the relationship between the parents, leaving the teenager in the outside position and relatively free from the tension between the parents. When the relationship system is relatively calm, the outside position is less comfortable, and the outsider will make some effort to draw another out of a perceived closeness with a third and create a new close twosome with him-or herself. For example, a daughter sensing an outside position with her mother can gossip with her mother about the mother's sister, her aunt. Mother and daughter form a close temporary alliance focused on the shared perceptions of the aunt. Tension now shifts to the relationship between the aunt and the mother. There are myriad variations of these basic triangling patterns that can be observed to predictably occur and reoccur in a particular family in conjunction with levels of tension. When the effects of anxiety, stress and ultimately tension cannot be managed within a single triangle, one of the threesome approaches a fourth, creating an exponentially larger set of triangles through which various inside and outside positions allow the effects of the tension to be managed with as little impairment as possible to any given person.

4.4.3. Family Projection Process

An important triangle involves parents and a child. Among a group of siblings, generally one child appears to be more emotionally involved with the parents than the others. That child monitors tension in the parents, responding to increases in that tension with shifts in behavior that draw the worried attention of the parents. The parents, equally attuned to the child, focus anxiously on the child. In that worried focus, the parental tension decreases as the parents appear to cooperate in order to address the "problem" in the child.

For example, a mother of three worries frequently about her oldest child, a son. She perceives him as less able to look after himself and in need of her guidance. She and the father, who shares the viewpoint, attempt to remove challenges from the son's path, fighting his battles for him, interpreting his actions to others, attempting to prop him up and shield him from distress and from failure. The son reciprocally presents himself as frail and incompetent, reinforcing the parents' perspective. The parents see the other two children as more robust and competent, and they have less worry about their development and life choices.

The relatively fixed nature of this particular triangle constrains a child's separation from the parents. The child in this position emerges from the developmental process with a less well-developed level of differentiation of self than his or her siblings. Bowen singled out this particular triangle as a central mechanism in the transmission of varying levels of differentiation of self from parents to children and called it the family projection process. Said somewhat differently, differential parental involvement with their children transmits varying levels of differentiation of self to the next generation.

4.4.4. Cutoff and Contact in the Multigenerational Family

A broad pattern concerns the connection between generational units in the extended family. The connections between parents, their grown children and their grandchildren reflect the experiences of the family system over time. The degree of connection between a nuclear family and its extended families appears to play an important role in the functioning of a nuclear family [1]. Families vary significantly in the degree of connection maintained with their extended families. Some are in good contact broadly across generations. Others maintain infrequent and limited contact with duty visits occasionally. Yet others display full cutoff with no contact whatsoever. Where families retain good connection and contact between generations, nuclear families appear to develop fewer dysfunctions or symptoms than in families where connection is weaker [13].

4.5. The Effects of Stress on Relationship Patterns

Much like the predetermined movement sequences of a dance, these patterns emerge and recede in the family marking surges in stress and anxiety. Some appear and shift rapidly in a dynamical kaleidoscopic fashion. Some patterns become fixed, losing their flexible response capability. As patterns become more fixed, participating family members appear more susceptible to the development of symptoms. With study and experience, an observer can predict the emergence of sets of reciprocal patterns within a specific family. While the issues or challenges (content) of the family shift across time, clinical observations suggest that the response patterns (process) appear to repeat in their linkage with varying degrees of tension in the family.

4.6. The Clinical Approach

The clinical efforts derived from family systems theory aim to assist the functioning of the family unit and not simply the behavior of a symptomatic individual. The clinician and the family work to shift focus from the individual family member to the context and processes of family relationships. Families are encouraged to observe first how the family system behaves and the conditions of that behavior. Who is involved, where does the interaction occur, what happens, and when does it happen? Facts become important, and people work to separate factual information from opinion and belief.

Motivated family members begin to identify reciprocal and repetitive patterns of interaction in which a particular symptom or difficulty is embedded. The family member attempts to recognize and slowly modify his or her own automatic participation in that pattern. He or she works to remain present in the tense relationships by managing his or her own emotional reactiveness to others. He or she develops plans for the management of self in family process and to follow through on those plans. Small sustainable changes in one's own functioning become the goal. Such small shifts appear to have long range effects on the functioning of the FES.

Family systems therapy, based on this model, brings the potential of natural systems thinking about the family to the domain of psychiatry and the helping professions. The principles and method generalize to other large groups and organizations where consultants and coaches attempt to apply systems thinking to their work.

5. The Potential of Natural Systems Thinking for the Human Condition

5.1. Principles of Functioning in the Family System and Other Natural Systems

Natural systems thinking in the Bowen theory has advanced our understanding of the family as an emotional system. It has illuminated how the family emotional system produces problems of health, behavior, and relationships. Principles for guiding behavior have emerged from this systems view to ameliorate the emotional and behavioral processes in the family that produce problems that originate in the family. The principles of how the family emotional system functions also appear in patterns of functioning in other natural systems. It is hypothesized that the family system and how its co-regulation of parts and the whole could serve as a model for scientific theorizing and research into other natural systems beyond the family. Knowledge of human systems could benefit in turn from what is learned about what is the same and different in other natural systems. This is what is referred to as natural systems thinking and it is consistent with Bowen's vision for a vibrant science of human behavior that could guide progress in psychiatry, medicine, and other applied disciplines.

Bowen identified a predictable relationship between how the family unit functions and the adaptiveness or level of functioning of each of its members. When similar processes between the social group and its members are observed in other natural systems it contributes to the progress in science that E.O. Wilson calls consilience. Consilience occurs when observations "jump together" across the boundaries of scientific disciplines and become the basis for a solid theory that integrates existing knowledge to provide a strong foundation for ongoing investigation and discovery [14]. The evolutionary biologist Ernst Mayr wrote that scientific progress is based more on progress in conceptualization than it is on new facts [15] (p. 23). Along this line, Bowen believed that schizophrenia and severe emotional illness would not be fully understood until the biological and social science disciplines could all be understood within a single frame of reference.

Bowen also believed the study of living systems would lead to an overarching natural systems theory ([1] p. 46, p. 354 and [16]). He went on to bring together two broad classes of behavior recognized in psychology and the behavioral sciences—reflexive and stimulus bound behavior and behavior with greater flexibility that is potentially under the individual's control [17–19]. The scale of differentiation concept reflects people's variation in the mix of these two classes of behavior and the corresponding differences in their levels of adaptive functioning. Questions for research include how the concept of differentiation relates to adaptive behavior in other species and to what extent the concept of differentiation of self in the emotional system can serve as an integrative framework for the study of interactions between the functioning of the individual and the group across the range of adaptive behaviors in the behavioral sciences.

Principles regulating interaction of individuals in social units of other species appear to be based on processes related to the individuality and togetherness processes observed in the human family system [1]. In the human family, behavior driven by emotional reactiveness in relationships reflects family togetherness pressures that erode the emotional autonomy, self-regulatory capability, and thoughtfully guided behavior of family members. If that erosive process goes too far, the viability and stability of the entire family becomes compromised. Evolutionary biologist John Bonner surveyed species from amoebae to humans looking at the integration and isolation of organisms from the larger groups of which they are a part. He observed across all the levels of life he studied, that the viability of individuals depends on their functional integration as part of the larger system and that the viability of the group depends on the functional integrity of its individual constituents in the larger system [20] (pp. 229–246). Both the loss of connectedness and too much of it undermine the functioning of the whole and its parts.

The attrition of individual fitness of some that benefits the functioning of others and the group as a whole appears to operate in other social species as well, especially when stress increases the intensities of relationship patterns. In the human, some family members absorb the family tensions and are more vulnerable to breakdowns and clinical symptoms. This leaves others in the family freer of the tensions and able to function at a higher level, which benefits the group. This channeling of tension in the system towards some more than others is common in both human societies and other primate social groups that transfer anxiety, often to reactive or isolated individuals who are lower in a stable social hierarchy [21]. This process of channelizing stress reactivity is found in natural systems far removed in evolution from the human. The process can be found in principles that regulate the functioning of slime mold amoebae. When the individual slime mold amoebae congregate, those that are more reactive to adaptive stresses as they increase become non-reproductive individuals. These individuals die as they form a stalk that supports the fruiting body of the collective where other individuals survive and reproduce [22,23]. Many relationship processes in other species seem closely related to principles of functioning that underlie the human family and also lead to variation in levels of adaptive functioning within and between functional units of social systems in nature [24].

5.2. Principles of Functioning in The Family System and Society

Natural systems thinking about the family has produced a way of understanding the conditions under which successful relationships and high levels of functioning are sustained for more family members. Viable relationships with the larger extended family can help the family to manage anxiety. The larger the whole network of interlocking triangles, the greater number of pathways for the transfer of anxiety to move in the system without fixing upon and impairing any one family member or relationship. This is one way that the intactness of the whole extended system impacts the individual. Additionally, the automatic tendencies to polarize and cutoff can be moderated and the advantages of connectedness sustained when the relationships are based on differentiation of self. With increased levels of differentiation, relationships are more likely to be maintained even when stress strains relationships and anxiety is heightened. With the broader view characteristic of higher levels of differentiation, thinking predominates over emotional reaction. Relationship tensions are taken less personally, blame is assigned less freely, and tolerance of difference is achieved more readily. Clinical experience has provided persuasive evidence, in addition to Bowen's original observations, that individual efforts toward increasing one's level differentiation in the family contributes to the moderation of relationship reactivity and improves the chances for stability and flexibility of the family system as a whole [1].

Bowen theorized that the same emotional forces that operate in the family operate in larger society in his concept of societal emotional process. The balance of individuality and togetherness forces that constitute the level of functioning or level of differentiation in the family also constitutes the level of functioning of society. It is proposed in the theory that the way society has been interacting with nature has resulted in the degradation of the natural environment upon which we depend. As a result, chronic anxiety in society has been increasing. In society as in the family, increasing levels of emotionally reactive patterns of functioning and decreasing functional levels of differentiation produce social regressions, all of which occurs under conditions of sustained chronic anxiety. As societal levels of chronic anxiety increase family levels of anxiety also increase. The projection process is further activated in the family and negatively impacts the adaptive maturation of the younger generation. Evidence that these negative impacts are occurring is found in the rather astounding report that 75 percent of Americans aged 17 to 24 did not meet the requirements to join the United States military in 2009. That is, 26 million young Americans, because of inadequate education, criminality, overweight, obesity and physical and mental health problems did not qualify for military service [25].

Knowledge of the principles of functioning of the family emotional system contributes options for the human to chart a course through increasing chronic anxiety arising from increasingly threatened and threatening natural systems. It provides principles of functioning directed toward management of self in relationship to others and using knowledge of emotional systems to guide behavior for the common good. These are the principles of functioning towards differentiation of self in the emotional system that are well known to clinical practitioners of Bowen theory. They aim to increase the functioning levels of individuals and the larger systems of which they are part and to counter the emotionally regressive impact of chronic anxiety on relationships and individual functioning in the family and society.

Understanding individuals and their groups as emotional systems in which the constant reiteration of individual emotional functioning impacting the group which impacts the individual back in return, provides a basis for the human to change the future. Larger scale societal change is theorized to be possible if enough key leaders will take on working on their own differentiation of self as a way to influence the larger systems of which they are a part. The challenge is to shift out of automatic emotionally reactive behavior patterns in spite of the chronic anxiety fueling them, towards thinking and actions based on responsible principles for the long term. This is also what we mean by systems thinking and what we believe is the potential of systems thinking for the human condition.

Author Contributions: All four authors contributed to the conceptualization and editing of this article. Each were responsible for particular sections, which were then integrated within the article.

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

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Article

Modeling Isomorphic Systems Processes Using Monterey Phoenix

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Received: 1 April 2018; Accepted: 24 May 2018; Published: 28 May 2018

Abstract: This article describes preliminary research (a proof of concept test) on the potential value of formalizing Isomorphic Systems Processes (ISPs) based on systems science research using the Monterey Phoenix (MP) language, approach and tool. MP is a Navy-developed framework for behavior modeling of system, process, and software behaviors, and has a demonstrated ability to expose emergent behaviors in engineered, complex systems. In this article, we introduce the related lines of research and discuss and demonstrate use of MP in modeling ISPs. We accomplish the demonstration through a small example of the Cycles ISP and discuss several possible variations generated from an MP model of this single ISP. Among these variations, we found patterns of oscillation, lifecycle, recycling, positive reinforcement, negative reinforcement, and combinations thereof, all derived from a common model of a cycle comprising six lines of MP code. Although the detection of three of these patterns (oscillations, lifecycles, and recycling) was anticipated, the involvement of the other two patterns (positive and negative reinforcement) were not anticipated in pre-model analyses and provided evidence to resolve a dispute over the application of ISPs in systems engineering. From conducting this initial experimentation at the intersection of different research domains, we found that using MP to formalize relationships within and among presently non-formally-described ISPs yielded new insights into system processes.

Keywords: isomorphic systems processes (ISPs); Monterey Phoenix (MP); behavior modeling; emergent behavior; cycles and cycling; systems processes theory (SPT)

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1. Introduction

This cross-cutting research lies at the intersection of systems science, systems engineering (SE), and software engineering. Systems Processes Theory (SPT) [1–9] is both a candidate general systems theory and systems science. This article describes the use of the SPT as a foundation to build a formal model of cycle behavior using Monterey Phoenix (MP) [10–28], an approach and language implemented for systems and software behavior modeling, verification and validation. This preliminary research is a first test of concept of the potential for the application of MP software to enable SPT basic research and enhance the foundations of SE by identifying and incorporating a better understanding of complex systems from the system sciences and general systems theory.

1.1. Research Objective

There is an inherent contradiction in the term "systems science" that is not often honestly admitted to or described. To be a science is to be comprised of relations that can be and are tested. In fact, testing is of particular importance to practical engineering as well as the natural sciences. Engineering disciplines have established tools for examining their particular scale and type of system, but, in general theories of systems, one is dealing with high-level abstractions of real systems. Most of the knowledge about how processes work or do not work to establish stable systems has come from comparison of real systems that have been elucidated via experimental testing. This knowledge may have been distilled from comparing many systems, but the comparisons are still abstractions often expressed in natural language, not formalized equations. To our knowledge, none of the many general theories of systems beyond those that are purely mathematical have been tested. This research aims to answer the question, "How do you truly test abstract models of system processes?" Achieving this "testability" would be a first for systems science with many downstream applications.

The MP framework for behavior modeling [10] is used to explore this research question because of its ability to express behaviors ranging from simple to complex at a high level of abstraction, and generate many different example instances of behavior from a single specification. We aim to model and simulate one well-studied system process—a cycle—at a very high level to test MP's potential application as a practical tool for advancing our understanding of system processes, like cycling, that manifest in many domains (Isomorphic System Processes, or ISPs) although they are often called by different domain-specific names (discipline-specific synonyms, or discinyms) [9]. Having a tool that enables the study of processes in terms of their domain-independent common properties would enable insights gained at the higher abstract level to be made available at the application level in every domain in which the process manifests. Such a capability would provide system scientists with a means to test their understanding of ISPs and further develop an ISP taxonomy with assistance from a formal reasoning tool. This article reports on the results of our experiment with cycle modeling, in which we applied MP to see if it could not only provide "mini-models"—small example instances of cycles—but also lead to significant new general knowledge about cycles using automated formal reasoning tools.

1.2. Systems Processes Theory

Circa 2010, the Systems Science Working Group (SSWG) of the International Council on Systems Engineering (INCOSE) officially started two ongoing research projects. Review of the available literature in the basic systems sciences indicated that there were many competing theories on systems but no unified or consensus theory. The SSWG recognized the importance of strengthening SE with a foundational theory of systems, but the existence of many fragmented theories, some not based on science, did not provide what was needed. Thus, the goal of the first project was to help unify that field by critiquing and expanding the SPT [1–3] as an integrated theory of "how systems work" for use in SE. The goal of the second project was to assemble and integrate complementary information on "how systems don't work." The lead for these two projects, Troncale, suggested that this second project should focus on recognizing and starting a new discipline called "Systems Pathology" [4–6] to identify, understand, document, and emphasize that there are common and repeating ways in which systems can fail to work. Subsequently, the INCOSE Foundation, in its first grants, provided seed funding to continue and extend both of these projects [7].

The SPT provided a strong, already developed, science-based general theory and candidate systems science to enable a jump-start for both projects. The natural system-based SPT claimed it provided the "prescriptive" part of systems approaches missing in most of the "systems thinking" and human-level approaches then popular in SE.

As a counterpoint to SPT, the existing state of awareness of systems in SE was characterized as focused solely on traditional systems thinking, which some argued was not systems science at all [29]. SE had a strong knowledge and use of systems thinking tools and system development programs, but the two projects suggested that this knowledge could and should be significantly extended by the strengths and extensive literature of the conventional sciences, just as chemical engineers study the fundamentals of chemistry as a foundation for their work or aeronautical engineers study math and physics. Furthermore, Comparative Anatomy, Comparative Physiology, Comparative Speciation, and Comparative Genomics were very successful because they compared across differences—an approach used by SPT in search of fundamental knowledge about systems that can only come from attempting to match and perceive commonalities across differences. SPT called this approach or method Comparative Systems Analysis (CSA). The SPT research of the INCOSE SSWG for the above purposes has expanded to some 20 collaborative projects [8], each involving cooperation between systems engineers and systems scientists to extend SE awareness of the results of the empirical sciences and distill them into *patterns* (how systems work) and *pathologies* (how systems don't work), common across all natural and human systems. One team is even establishing a new professional society, the International Society for Systems Pathology (ISSP) to help several currently isolated domains learn about each other's discoveries, share, and unify the knowledge base.

The SPT distills its insights from examination of a wide range of systems theories and natural science experiments [2]. Example experimental domains include physics, geology, astronomy, chemistry, biology, mathematics and computer science, and lately SPT has added comparisons of these natural phenomena with the engineering and human domains. Each domain contains system processes that are described in the language of its home domain. This research builds on the SPT premise that there exist *isomorphic* system processes (ISPs) [2] that remain constant across many domains, and that these ISPs can be expressed as domain-neutral concepts to reveal insights about how systems work in general. ISPs are termed "isomorphic" because they are found across many, if not all, mature systems and so they are iso- (same) and -morphic (form). (Note that this is quite a distinct use of the term from its use in mathematics). The term "systems" is used because ISPs are hypothesized to be the fundamental mechanisms by which the sustainability of systemness is achieved; that is, they are the minimal steps for maximal efficacy to achieve system function/purpose no matter what the scale or compositional parts of the system. ISPs are termed "processes" because they perform a similar function/purpose across all these systems by the same "process steps" or developments in an obligate sequence.

For the MP modeling test of concept, therefore, the team decided to select one widespread pattern, "Cycles", from 110 patterns available from the SPT body of work. Some patterns that appeared to be variants of cycling were part of the discussion that grouped the 110 proposed ISPs resulting in a more concise list of 55, since some of the initially considered system processes were essentially different instances of the same pattern [2]. This grouping came about by recognizing in many instances that some ISPs were actually discinyms, or discipline-specific synonyms, for the same process. Troncale argued on abstract grounds that aspects of cycling were shared by a very wide range of diverse phenomena in nature (and humans), in which different cases exhibited many of the same identifying features of cycles. These included phenomena such as oscillation, recycling, iteration/recursion, spin, solitons, waves, hypercycles, and lifecycles. However, at this stage of development of the SPT, only abstract reasoning, that is, comparisons across real natural systems from the results of their science experiments, expressed as informal linguistic-based representations informed the endless discussions and debates that ensued.

MP version 1 first became publicly available in 2015 on firebird.nps.edu, and was shortly thereafter noticed as a tool that could potentially inform these discussions in a more formal manner. Since cycles are present in literally hundreds of phenomena of the natural sciences at all scales and also found widely in human systems, any elucidation of cycles as an ISP using more formal models would significantly contribute both to engineering systems and to the theoretical knowledge of systems, so improve theory and praxis simultaneously.

Recent research by Quartuccio [28] has suggested that the presence of similar patterns and pathologies (the latter being sometimes called *anti-patterns* in systems and software engineering vernacular) in different domains (e.g., medical and aviation) can be identified, analyzed, and documented using MP. This work also contributed inspiration for potential practical applications of modeling SPT patterns or pathologies at a high level of abstraction in MP.

1.3. Monterey Phoenix

While these SPT research projects were evolving in the INCOSE SSWG, a new formal approach and language for system and process behavior modeling known as Monterey Phoenix (MP) was also taking shape and circulating for peer review in the software engineering community. MP is a Navy-developed behavior modeling framework composed of a formal language, a lightweight formal methods approach, and an automated tool that generates a "scope-complete" set of possible event traces from a behavior model using each of the former. For MP, "scope-complete" means exhaustive up to a maximum number of event iterations specified by the user, a defining feature of the MP approach and formalism to make an otherwise infinite model finite for simulation, and therefore practical for testing behaviors up to a given scope. MP is used to define logical or physical objects in terms of their underlying behaviors. Behavior is defined as set of events with two fundamental relations: precedence (for event sequencing) and inclusion (for event decomposition). Behavior rules can be composed from these two basic relations using event grammar that allows for concurrent, alternate, optional, and iterating events, as shown in the upcoming examples.

MP was initially conceived and developed for modeling and assessing software architectures [11,12], but it captured the interest of systems engineers when it became clear that MP provides not only a framework for software modeling, but for systems in general, including humans, organizations, hardware, software, and environment behaviors [10,13–28]. MP provides for modeling high-level behaviors belonging to a range of system types from living to artificial and from natural to technological in nature. For example, we can model the behavior of cells, humans, animals, robotics, air and spacecraft, ground vehicles, information technology systems, environmental activity, etc., and interactions among these systems, in MP. We model systems as independent entities—defining each as a separate root event in MP—that interact through stated dependencies that are coordinated through codified natural law or design specifications. The MP event grammar provides a lightweight formal language for expressing behaviors at the level necessary to test the modeling of an ISP.

Using event grammar capable of describing anything that has behavior at a high level of abstraction, MP has been employed in thesis, dissertation, and sponsored research efforts to model behaviors for system architecture, software architecture, software-intensive systems architecture, business processes, human interactions, medical procedures, operational missions, and entertainment events [30–46]. The precise language enables humans to describe potentially infinite combinations of system behavior in a concise and finite model, and then generate a scope-complete set of example instances of behavior from that model. Once this set of behaviors (scenario instances in the form of event traces) is generated, each instance can be tested against behavior expectations through the use of manual inspection as well as automated queries and assertion checking [10], providing a scientific basis for reasoning about system behaviors, including refutation of claims about system behavior. What sets MP apart from other behavior modeling approaches is its foundation in lightweight formal methods as a basis for these queries, assertion checking, and reasoning about behavior models. In particular, the following section further describes and illustrates what model "scope" means, how defining a scope for behavior models is different from current behavior modeling approaches, and the advantages and limitations of modeling up to a scope.

1.4. The Meaning of "Scope" in MP Behavior Modeling

Model "scope" is a key feature of the lightweight formal methods upon which MP is based. Lightweight formal methods for scenario generation [47] came into being to make an alternative available to traditional heavyweight formal methods such as model checking and theorem proving. Lightweight and heavyweight formal methods differ in scope of completeness, usability, cost, and experience required. Heavyweight methods mathematically guarantee exhaustive scenario coverage, and so are functionally attractive for mission-critical system design. Traditional formal methods are comparatively expensive and require specialized skills. Lightweight formal methods, on the other hand, trade away the 100% completeness guarantee for greater usability (lower entrance barrier to use) and faster results, while providing increased coverage over popular informal methods. MP uses lightweight formal methods and the concept of scope to denote the boundary for the included behaviors. Scope in MP is the upper limit on how many times an event should repeat, if it is on a loop. Thus, all MP models are run *for a given scope*, which places an upper bound on the number of event iterations to repeat. For example, running at scope 1 will execute iterating events up to one time, running at scope 2 will execute iterating events up to two times, running at scope 3 will execute iterating events up to three times, etc. This scope limit enables an otherwise infinite model to execute in a finite amount of time, trading completeness for speed and ease of use.

1.5. MP Modeling Environment and an Example Illustrating the Concept of Model Scope

An MP modeling environment called MP-Firebird is available publicly at http://firebird.nps.edu. As seen in Figure 1, the upper left pane of MP-Firebird consists of a text editor for MP code, into which the user types a model or loads an existing model previously composed. The lower left pane is a console window that logs statistics about the trace generation process as the model is run. The center pane contains a large view of the selected event trace graph generated from the model, and the right pane contains a thumbnail list of all traces for the given schema at the given scope. Run scope in MP-Firebird is controlled by using the slider bar to the right of the Run button.

The model displayed in the figure is a pre-loaded example of a simple message flow, available from Import > Load example > Example_01_simple_message_flow. The MP code in the text editor describes two root events called `Sender` and `Receiver`, each performing its respective `send` or `receive` activity. The `(* ... *)` parentheses surrounding each event means that the contained event iterates zero or more times. The `COORDINATE` statement is a separate constraint on the events in each root to enforce a precedence relation to exist between events `send` and `receive`. (Without this constraint, no dependency would exist between `send` and `receive` events and `send` could occur without `receive`, and `receive` could occur without `send`).

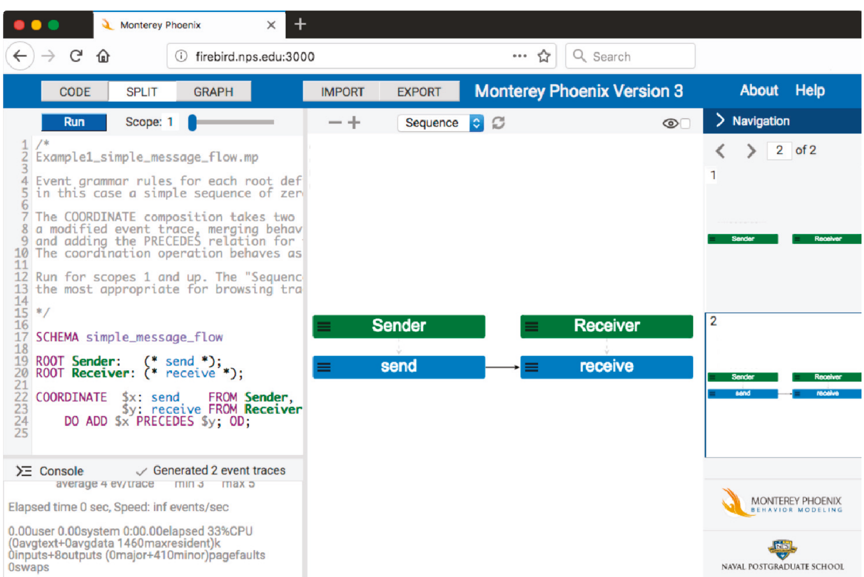
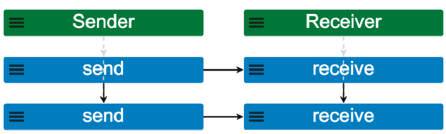


Figure 1. The MP-Firebird modeling environment at http://firebird.nps.edu, showing the pre-loaded MP model Example01_simple_message_flow run for scope 1.

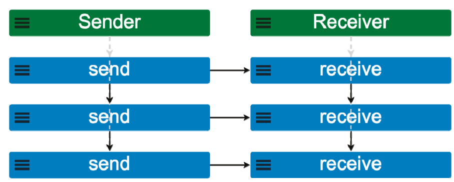
When the model is run up to a scope limit of 1, two event traces (scenarios) are generated consistent with the MP code. In the graphs produced, green boxes are used for root events, blue boxes are used for atomic events, dashed arrows are used to depict inclusion relations, and solid arrows are used to depict precedence relations. In trace 1, both the `Sender` and `Receiver` are idle since neither `send` nor `receive` occur (shown in Figure 1 top thumbnail on the right), and in trace 2, the `Sender` includes one `send` event that precedes one `receive` event in the `Receiver` (shown in Figure 1 center pane).

When the same model is run up to a scope limit of 2, the same scenarios that were present at scope 1 are generated plus a third trace showing the additional possibility that the coordinated send–receive events occurs two times (Figure 2a). Running the model up to a scope limit of 3 results in all scenarios from scope 2 plus a fourth trace showing the send–receive events iterating three times (Figure 2b).

The model in Figure 1 was run for up to scope limits 1, 2, and 3 to demonstrate how scope limit works in MP models. It is conceivable to run MP models for higher scopes, but run time increases dramatically with increasing model complexity. In general, lower scope settings produce fewer scenarios in less time than higher scope settings. Shorter run times are preferable to longer ones so that the model can undergo iterative refinement many times without unreasonably long waiting periods for the event trace generator to return results. The requirement for reasonably short run times begs the sensible question: "What scope limit is high enough to include most of the behaviors of interest?" The next section addresses this question with a heuristic called the Small Scope Hypothesis [47].



(a)



(b)

Figure 2. Pre-loaded MP model Example01_simple_message_flow scenarios from (**a**) scope 2, showing the scenario containing the new maximum of two iterations of send and receive (trace 3); (**b**) scope 3, showing the scenario containing the new maximum of three iterations of send and receive (trace 4).

1.6. Use of the Small Scope Hypothesis

Running the model at a low or small scope has advantages in speed, but are we missing important information by excluding examples from higher scopes? Our observations have been such that scenarios appearing at higher scopes are generally present in some shape at the lower scopes as well. These observations are consistent with Jackson's Small Scope Hypothesis, which states that most errors can be exposed in small examples [47]. Browsing at scope limits of 1, 2, or 3 has often resulted in very valuable and surprising observations about our modeled system, many of which we would have missed by using traditional methods alone; but browsing at scopes 4 and above produced more traces at the expense of longer generation times and more complex graphs, but no new insights than were already gathered at scopes 1–3. Discussion of the Cycles ISP model in the sections that follow therefore provides specific examples of general patterns that can be detected at low scopes of 1–3.

2. Materials and Methods

The SPT research products are rich in details and examples of both patterns and pathologies. SPT presents a minimum of 55 classes of candidate system processes condensed from an initial list of 110 individual and distinct system processes [2]. All need further evaluation and development. A set of 30 information categories for each ISP has been created to document, extend, and enable teaching and application of SPT-ISPs [5]. To simplify this initial "test of concept", this research examines just one of the 110 system processes using just four of the 30 information categories (Features, Functions, Processivity, and Measurables). We decided to use the MP formal behavior modeling language in order to determine if further research in this direction is warranted.

Source data for the Cycles ISP MP model came from the body of work on cycles in SPT research, in particular from [9]. From this source information, we created a simple but formal model of Cycle behavior using the MP event grammar. We conducted all experiments with this model using the publicly available MP behavior modeling tool, MP-Firebird, at http://firebird.nps.edu. MP-Firebird was used to compose, execute, and refine the Cycles ISP model to embody the identifying features of a cycle. Example outputs of this generation are illustrated and described in the sections that follow. The full set of model outputs can be reproduced by running the illustrated code on MP-Firebird.

2.1. Cycles ISP Model, Version 1

A basic MP model of the Cycles ISP was first composed as a sequence of one or more steps that move the cycle either forward or backward:

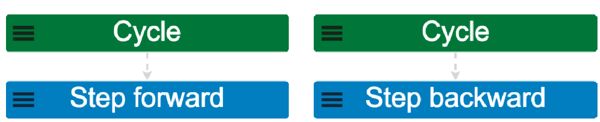
```
SCHEMA Cycle_ISP_v1
ROOT Cycle:  (+ ( Step_forward | Step_backward ) +).
```

The `SCHEMA` declares the name of the model (`Cycle_ISP_v1`). The `ROOT` establishes a main event, in this case, a `Cycle`. The `Cycle` event includes one or more (`+ ... +`) repetitions of `Step_forward` or `Step_backward` (the "or" operation is denoted by `|`).

Note that `Step_forward` and `Step_backward` may have synonyms such as `Move_up` and `Move_down`, `Move_in` and `Move_out`, and `Increase` and `Decrease`. The SPT research has demonstrated the existence of discipline-specific synonyms, or *discinyms*, which also may be used to name cycle movements according to a domain taxonomy.

2.1.1. Cycles ISP Model, Version 1, Scope 1

Running this preliminary model on MP-Firebird at scope 1 illustrates two possible outcomes (as event traces) for cycle behavior: stepping forward, or stepping backward (Figure 3). Immediately, we can tell that these event traces do not fit the definition of a cycle, since there is no repetition or recurrence, as called for in the earlier presented definitions. The depicted scenarios do not contain any repetition, and so only represent a part of cycle behavior.



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

Figure 3. Initial event trace outputs of the `Cycle_ISP_v1` model, run for scope 1: (**a**) Cycle steps forward; (**b**) Cycle steps backward. Neither scenario contains any repetition and therefore only represents part of a cycle's behavior.

To reject these event traces from the set of valid examples of a complete cycle, the following constraint is added to the model:

```
ENSURE #( Step_forward | Step_backward ) > 1.
```

Running the constrained model at scope 1 will now generate zero valid traces, having the intended effect of removing single-iteration behaviors from the Cycles ISP model.

2.1.2. Cycles ISP Model, Version 1, Scope 2

Running the constrained model at scope 2 illustrates four possible outcomes for cycle behavior (Figure 4). The cycle may step forward twice, step forward then backward, step backward then forward, or step backward twice. Each scenario contains movement, then another movement, and so each is a valid, albeit general, example of a cycle.

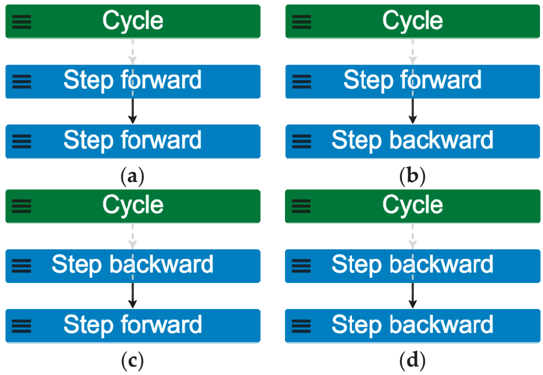


Figure 4. Outputs from the constrained `Cycle_ISP_v1` model, run for scope 2: (**a**) Cycle steps forward twice (trace 1); (**b**) Cycle steps forward then backward (trace 2); (**c**) Cycle steps backward then forward (trace 3); (**d**) Cycle steps backward twice (trace 4).

2.1.3. Cycles ISP Model, Version 1, Scope 3

Figure 5 shows four of twelve scenarios that were generated at scope 3. The output was inspected by browsing the generated event traces one at a time in the MP-Firebird tool by scrolling down the navigation pane (shown on the right side of Figure 1) and clicking on each event trace to enlarge it in the center pane. Patterns started to become visible in the scenarios: Figure 5a positive reinforcement and Figure 5b negative reinforcement are clearly present in the consecutive repeating selection of `step_forward` or `step_backward`, respectively. The scenario in Figure 5c clearly illustrates a pattern of oscillation, with `step_forward` followed by `step_backward` followed by `step_forward` again. The scenario in Figure 5d shows an instance where two patterns (positive reinforcement and oscillation) are present in the same scenario.

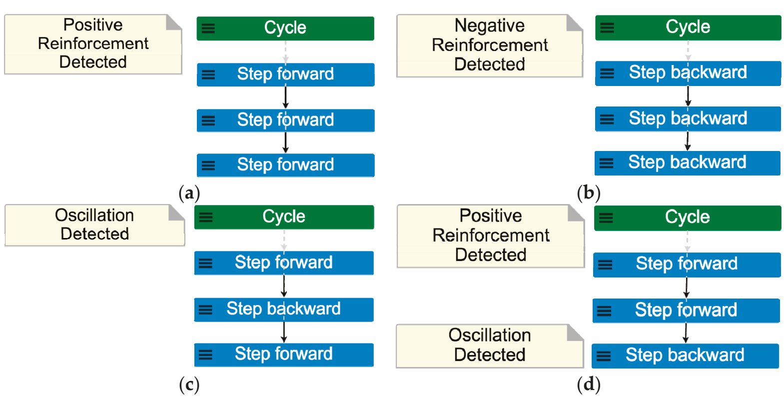


Figure 5. Example outputs from the constrained `Cycle_ISP_v1` model, run for scope 3: (**a**) Cycle exhibits a positive reinforcement pattern (trace 5); (**b**) Cycle exhibits a negative reinforcement pattern (trace 12); (**c**) Cycle exhibits an oscillation pattern (trace 7); (**d**) Cycle steps forward twice then backward once (trace 6).

Once the modeler identified the presence of a pattern in a trace, a condition was written to automatically annotate every trace containing that pattern. The graphs in Figure 5 include comment boxes that were automatically placed on the pertinent scenarios.

To automate the graph annotations, conditions are added to the model. For example, the following condition annotates all traces containing positive reinforcement:

```
IF EXISTS DISJ $a:  Step_forward, $b:  Step_forward
                $a PRECEDES $b THEN
                    SAY ( "Positive Reinforcement Detected" ); FI.
```

Likewise, graphs containing negative reinforcement are annotated using the following condition:

```
IF EXISTS DISJ $a:  Step_backward, $b:  Step_backward
                $a PRECEDES $b THEN
                    SAY ( "Negative Reinforcement Detected" ); FI.
```

Finally, the following condition annotates all traces containing oscillation:

```
IF EXISTS DISJ $a:  Step_forward, $b:  Step_backward
                $a PRECEDES $b OR
                $b PRECEDES $a THEN
                    SAY ( "Oscillation Detected" ); FI.
```

These annotation rules are also formal specifications for the definition of the respective pattern. They provide the means to discuss and debate the precise meaning of each pattern.

Recall that the inspection process is based on the premise that most behaviors of interest (patterns or pathologies, in the case of this research) can be exposed on small examples, which is based on Jackson's Small Scope Hypothesis [47]. If we run the model at a higher scope, we would see the possibilities of hundreds or even thousands of repetitions involving positive reinforcement, negative reinforcement, and oscillation. These small examples demonstrate that it is not necessary to run many repetitions (high scopes) to detect these patterns; scope 3 was sufficient to produce examples of these patterns.

2.2. Cycles ISP Model, Version 2

The model is further refined to explore additional possible cycle patterns. We added an initial condition prior to the repetition steps, and an end condition after the repetition steps. The initial and final conditions may also occur one or more (+ ... +) times. The entire `Cycle_ISP_v2` model, along with annotation conditions (lines 30–53), is depicted in Figure 6.

2.2.1. Cycles ISP Model, Version 2, Scope 2

As in version 1 of the model, version 2 has zero traces at scope 1 due to the `ENSURE` constraint (line 26 in Figure 6). Executing the model at scope 2 produces 40 possible scenarios, two of which are illustrated in Figure 7. Scenario (a) shows an example of a positive reinforcement pattern in the first lifecycle, and an oscillation pattern in the second lifecycle. Scenario (b) shows an example of a negative reinforcement pattern in the first lifecycle, and a positive reinforcement in the second lifecycle. Both scenarios are examples of recycling, in which one lifecycle concludes (first `End_condition`) and another begins afterwards (second `Initial_condition`). Both scenarios also contain patterns nested within other patterns. Thus, we see how a small, minimal MP model of a cycle can lead to potentially thousands of process combinations, before constraints are added to shape, govern, or otherwise bring order to a system's behavior.

```

SCHEMA Cycle_ISP_v2

ROOT Cycle:      (+ Initial_condition
                    (+ ( Step_forward | Step_backward ) +)
                   End_condition +);

ENSURE #( Step_forward | Step_backward ) > 1;



/*Check for Positive Reinforcement Template */
IF EXISTS DISJ $a:  Step_forward, $b: Step_forward
            $a PRECEDES $b THEN
                SAY("Positive Reinforcement Detected"); FI;

/*Check for Negative Reinforcement Template */
IF EXISTS DISJ $a:  Step_backward, $b: Step_backward
            $a PRECEDES $b THEN
                SAY("Negative Reinforcement Detected"); FI;

/*Check for Oscillation Template */
IF EXISTS  $a:  Step_forward, $b: Step_backward
            $a PRECEDES $b  OR
            $b PRECEDES $a  THEN
                SAY("Oscillation Detected"); FI;

/*Note Lifecycle Completion */
COORDINATE $a: End_condition
    DO ADD SAY("Lifecycle Complete") PRECEDES $a; OD;

/*Check for Recycle Template */
IF #Initial_condition > 1 THEN
                SAY("Recycle Detected"); FI;

```

Figure 6. The `Cycle_ISP_v2` model.

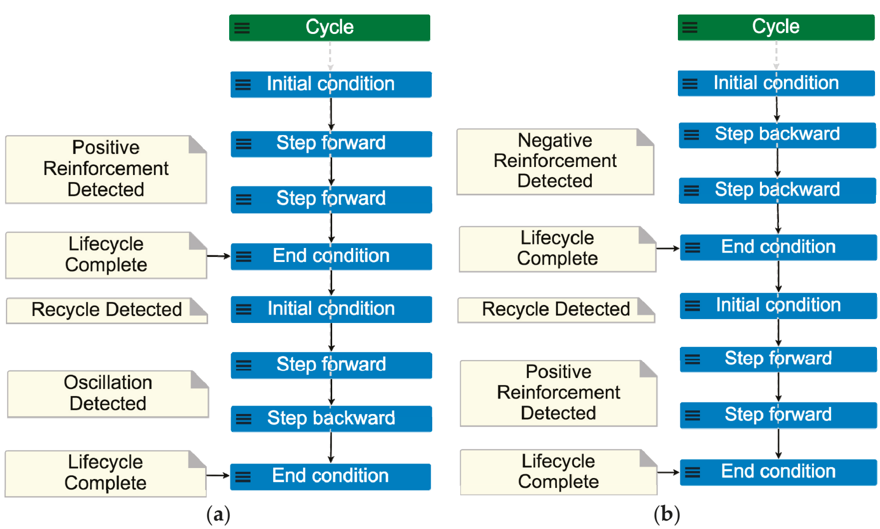


Figure 7. Example event trace outputs of the `Cycle_ISP_v2` model, run for scope 2: (**a**) Lifecycle 1 contains positive reinforcement and Lifecycle 2 contains an oscillation pattern (trace 20); (**b**) Lifecycle 1 contains negative reinforcement and Lifecycle 2 contains positive reinforcement (trace 37). Both scenarios contain the recycling pattern.

2.2.2. Cycles ISP Model, Version 2, Scope 3

There are 2952 cycle instances generated at scope 3, revealing many more possible combinations of the identified patterns. Running the model at scope 3 increases the number of cycle movements within the patterns exposed at scope 2. As the number of scenarios increase into the thousands, manual inspection becomes impractical. MP has assertion checking and querying tools to check these large data sets for properties of interest, but the Small Scope Hypothesis affords us the convenience of exposing many patterns and pattern combinations on a small number of examples that are also present among the large number of examples.

2.3. Example Applications of Cycles across Different Domains

The main criterion for identifying a process as an ISP is testing for its isomorphic nature. This requires looking at many types of systems and scales of systems; otherwise, it would not fulfill the criteria for a general theory of how systems work. For SPT, this means examining the experimental results of many sciences and abstracting out similar, common, identical, alike structures, relationships, and patterns from the particulars of each discipline to more general descriptions (abstractions) of the steps in the process that are true of all of the specific systems. Abstraction followed by comparison is the key. Are the generalized steps the same even though the particulars going through the steps are not?

In his 90-min online InfoLab© lectures on 14 of the ISPs (for a graduate course, Intro to Systems Science for Systems Engineers, SE 510) for the purpose of providing more details on SPT, Troncale cites and describes numerous case studies from the conventional sciences for each ISP. Each case study is from a phenomenon experimentally elucidated by one of the sciences. These included case studies of real, proven phenomena from Astronomy, Cosmology, Physics, Chemistry, Geology, Biology, Mathematics, and Computer Science as reported in the reductionist science literature. Recently, these have been expanded by additional case studies from the various Human Sciences, Engineering, and a category entitled, "interdisciplinary".

Specifically for the ISP Cycles, the aforementioned SE 510 lecture cited 87 case studies of cycling occurring in the above named sciences. To test the application of the Cycles ISP MP model in different domains, we selected four case studies from [9] and substituted discipline-specific event names from the case studies for domain-independent event names in the Cycles ISP MP model (Table 1). The four case studies selected were cell division, human diurnal activity, geological activity, and a beating heart.

Table 1. Event discinyms for four example domain-specific types of cycles.

Cycles ISP Event Name	Cell Model Event Name	Human Model Event Name	Rock Model Event Name	Heart Model Event Name
Cycle	Cell	Human	Rock	Heart
Initial condition	Initial condition	Initial condition	Initial condition	Initial condition
Step forward	Divide	Awake	Expand	Relax
Step backward	Not Divide	Sleep	Contract	Contract
End condition	End condition	End condition	End condition	End condition

After making the event name substitutions shown in Table 1, we ran the domain-specific MP models and obtained the cycle model scenarios for each domain. Figure 8 shows four examples of oscillation from different domains, each of which map onto the same Cycle model.

Note once more the effect of limiting the scope, to 3 in this case: only three iterations occur in each example, but it is enough for the oscillation pattern to be quite visible. Additional types of cycles and variants are left for exploration in future work.

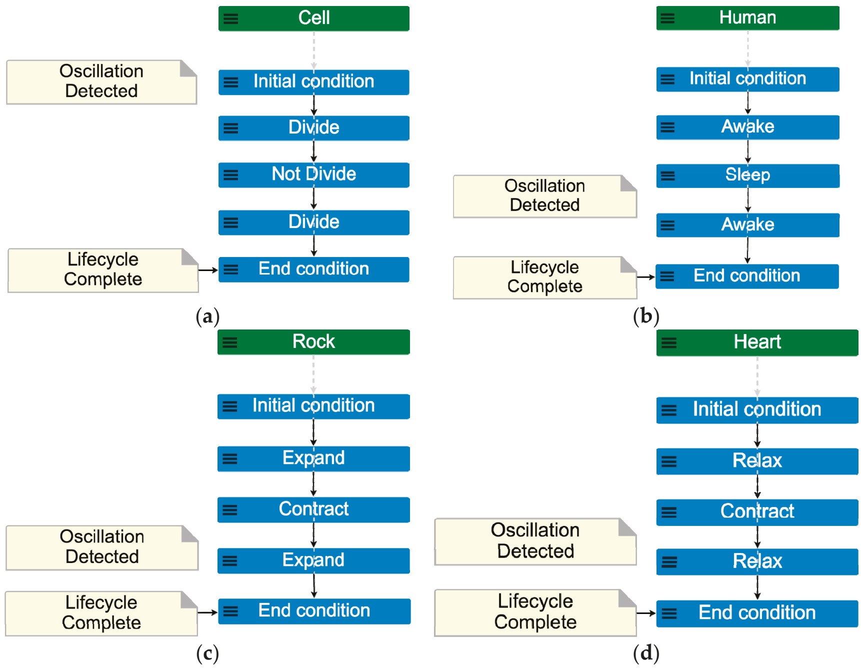


Figure 8. Example outputs from the constrained `Cycle_ISP_v2` model (trace 7 in each case), with discinyms substituted for `Move_forward` and `Move_backward`, and run for scope 3: (**a**) process of cell division; (**b**) process of diurnal activity in humans; (**c**) process of geological activity; (**d**) process of a beating heart.

3. Results

A simple formal model of the Cycles ISP starting with just two lines of MP code (version 1) exposed patterns of oscillation, positive reinforcement, negative reinforcement, and combinations thereof. Revisions to this model (version 2) contained six lines of code and exposed these same patterns plus additional patterns of lifecycle, recycling, and all combinations thereof. Table 2 provides the run statistics for the number of cycle examples produced at each scope and the scenario generation times on MP-Firebird.

Table 2. Cycles ISP MP model run statistics.

Model Version	Scope	Number of Scenarios	Generation Time (s) [1]
1	1	0	0.01
	2	4	0.01
	3	12	0.01
2	1	0	0.00
	2	40	0.02
	3	2952	1.81

[1] Macbook Air, macOS version 10.13.3, 2.2 GHz Intel Core i7, 8 GB 1600 MHz DDR3.

The number of possible combinations of unique cycle patterns is visible in the exponential growth in the number of scenarios as scope increases. From a small model of six lines of code, we see that thousands of cycle scenarios are possible. These numbers represent the exhaustive set of cycle model scenarios, providing full coverage of possible outcomes up to the indicated scope [10].

An objective of this research was to see if any MP behavior scenarios presented mini-models of previously discussed variants for the Cycle ISP. We indeed found patterns for oscillation, recycling, and lifecycles in the MP model of the Cycle ISP. We did not isolate patterns for waves, solitons, iteration/recursion, spin, and hypercycles during this initial effort, but these may become evident after further inspection or refinement of the model and consideration of different discinyms for event names. The act of modeling may raise significant new questions about these currently considered variants on cycling that challenge the SPT community's initial hypotheses of their being the same pattern as cycling. Constraining the list of variants on cycling would be an important advance in SPT and to applications of cycling to SE.

One surprising result from this research was the presence of both positive and negative reinforcements in the cycle examples. These were not anticipated or identified as directly associated with the Cycles ISP in previous SPT research. Cycles and Feedbacks are actually separate systems processes in the current consensus on SPT, if we consider positive and negative reinforcements as positive and negative feedbacks. SPT has linkage propositions that connect + and − feedback with oscillations, but this has been challenged by SE members of INCOSE in past International Workshop discussions. It appears models of real biological systems incorporate feedback to get oscillating behavior but that this is less known in the physical sciences. To have independently found them in MP event traces of cycling brings new information to the SE debate.

There is precedent for this development, from an MP modeling perspective. MP has delivered surprising scenarios before by containing unanticipated behavior examples in models by different users, of different systems, in different domains [33,37,39,41,44]. This research adds to the body of work showing MP's ability to illuminate unexpected emergent behaviors, and potential to be put to use for the SPT research.

4. Discussion

The results summarized in the previous section are discussed in more detail in the subsections that follow.

4.1. Complex Cycle Examples Arose from a Simple Model of a Cycle

The first significant finding from formally modeling a cycle in MP was that such a simple model of a cycle (on the order of six lines of code) could produce such an impressively large and diverse number of "cycle instances" (nearly 3000 unique instances of cycle behavior when the model is run at scope 3). A very simple model of a cycle gave rise to a large number of behaviors whose complexity increased with run scope. This supports the notion that simple rules exist at the foundation of complex behaviors, and suggests that if we can distill and formalize these simple system and process behavior rules, we can (to some extent) reproduce more complex system behaviors in simulation for study and comparison with actual systems. MP also provides a capability to check for the presence or absence of model properties of interest in large sets of simulation instances. In practical terms, this means that, if we know or suspect a particular cycle instance could occur, we can query the data set to see if there are any examples of it. MP modeling therefore provides the SPT community with a means for formally testing, verifying and validating ideas that have to date only been informally discussed, debated, and refuted without automated tools to support the discourse.

4.2. Cycle ISP Patterns Previously Discussed and Described Informally Were Inherently Present among the MP-Generated Examples

Upon inspection of these automatically generated instances, it became apparent that some of the instances inherently contained similar patterns. The patterns that emerged, in fact, matched many of the identifying features for cycles that had been informally discussed and debated as part of the ongoing SPT research, including oscillation, recycling, and lifecycles. These results provide an affirmation that the earlier SPT discussions on cycling pertaining to the recognition of oscillations, recycling, and lifecycles as related ISPs was warranted and supported by results of the MP runs. There is a significant extension of this result. Just as MP generates many versions of the original ISP process in computer "space", so also does nature in real systems generate many variants on cycling in real, dimensional space (e.g., through evolution). This MP feature could lead to the examination of the potential for generation of "artificial systems" de novo in computer space.

Furthermore, MP generated both singular and compound examples of patterns, i.e., examples that contained each pattern by itself, and patterns combined with or nested within other patterns. Moreover, because MP is exhaustive in its scenario generation, we can guarantee the set of examples generated contains every possible pattern combination expressible by the model up to the scope limit [10]. As discussed earlier, scope limit is a lightweight formal methods concept that places an upper bound on the number of event iterations in the model in order to limit the simulation run time. The Small Scope Hypothesis [47] is used as a heuristic to enable us to find most of what we are interested in knowing about cycles at a small run scope (typically scopes 1, 2, or 3). Cycle patterns that present at scopes 4 and 5 are also expected to present in some shape at scope 3. Prior experiments with run scopes [48] lend some confidence to this heuristic, but these current assumptions for MP can also be tested for the Cycles ISP model as part of follow on work.

By implication, the recognition of some known patterns in the generated example set suggests that several other possible variants on cycling should also be explored. Waves, solitons, iteration/recursion, spin, and hypercycles [9] are some of the other recognized variants of the Cycle ISP that were not observed in scenarios arising from the current Cycles ISP MP model, but the as-is MP model of a cycle provides a canvas for exploring how these variants could also possibly emerge from this model or from a revised model containing refinements informed by reasoning with MP tools. The Cycles ISP MP model lays the groundwork for follow on research to determine whether the aforementioned variants should be considered as the same thing as the Cycling ISP or as completely independent ISPs. Such experiments should support the development of a repeatable methodology for using MP modeling to inform SPT research on this question and across all the 110 candidate ISPs.

4.3. Positive and Negative Reinforcements Emerged in the Cycle Examples

Although the previously discussed patterns had been recognized and debated in SPT research, we did not even discover, recognize or debate the involvement of two additional behaviors until the MP modeling exposed them: namely, "reinforcements". Among the Cycles ISP MP model examples were completely unforeseen influences and essential participation of both positive and negative reinforcements as part of the process. Reinforcements have commonly known relationships with cycles, but we did not foresee them emerging in examples from the Cycles ISP MP model. Positive and negative feedback had been argued by one SPT cohort as necessary for oscillation to occur; however, other cohorts disagreed. The presence of these patterns could provide a basis for reasoning about how positive and negative reinforcements influence cycling, as well as what "reinforcement" actually means in models of real phenomena. This discovery opens the door to a further line of questioning: How can emergent patterns and behaviors like this inform the aforementioned debates? How were these cycling, and how likely was each instance? Should they each be explored as individual isomorphs, or be considered variations on each other? How many additional behaviors could MP discover for SPT for the other 54 or 110 ISPs?

4.4. Implications for Systems Science Research

Modeling SPTs using MP provides a promising virtual "systems laboratory" to examine billions of years of optimization or improvement or evolution of natural systems. The basic tenet of SPT is that the reason we now can see and empirically or experimentally prove the existence of common patterns (ISPs) is that all of these systems, composed of entirely different parts, originating at different times, at totally different scales, across many types of systems, solve their myriad challenges by "falling into" these common isomorphic dynamics or solutions. By definition, SPT models are prescriptive and not just descriptive. This is their distinction from other System Dynamics (SD), or Soft Systems Methodology (SSM), or Interpretive Structural Modeling (ISM) models. They do not compete with those; they should be added to those as the possibly prescriptive component.

5. Conclusions

The various teams working on SPT have been exploring SPT research as a candidate for a General Systems Theory (GST) and for systems science, both of which need a means for testing abstract models. This research answered the question, "How do you test abstract models of systems?" By modeling the Cycles ISP using MP, we were able to test and reason about cycles in a new and formal way, using automated tools to unravel and expose the inherent patterns within cycles occurring both alone and in groups. This paper thus established productive applicability of MP software to the SPT problem space, in which MP event traces could comprise a library of mini-models envisioned for each ISP.

Earlier discussions about cycles and other ISPs were based on natural language descriptions and informal models at best. None of the discussions were supported with formal models of behavior like the cycle model contained herein. MP was tried as a tool for generating mini-models of systems mechanisms that are general and discipline-independent. Cycle behavior was described as a set of step-by-step procedures—an algorithm—that was executable in computer space to see many possible instances and variants of cycles. These mini-models of cycle instances did generate additional information about cycles that had not been obtained to date by comparison of the real systems counterparts to the modeled mechanism (specifically, illustrating the connection of positive and negative reinforcements to cycles). It also demonstrated that many of the known cycle variants arise from a single compact formal specification of cycle behavior. The MP model of just one ISP was a source of new knowledge about the mechanism for that individual ISP, showing that MP is a productive framework for describing the Cycles ISP as a formal and executable model, in terms of a simple and straightforward event grammar.

The abstract Cycles ISP MP model shown in Figure 6 was tested in four different domains by adapting the event name language as shown in Table 1. The MP simulation results of each model "unraveled" specific instances of cycles that fit the patterns previously considered distinct ISPs. In Figure 5, we have evidence from the MP simulation runs that some ISPs previously considered as separate from cycles are in fact special cases of cycles. Figure 8 shows the oscillation pattern emerging from each of the four domain-specific cycle models tested, demonstrating the isomorphic nature of the Cycles ISP. MP provides automation to facilitate the study of how ISPs are related, and opens the door to future work in this area.

6. Future Work

Since the use of MP achieved both extension of our knowledge base of cycles and cycling and at the same time provided the means to test that knowledge base, we consider it a promising potential source of significant advancements in both general theories and specific applications. Future work will apply instances of the Cycles ISP in several different domains to generate more concrete examples of where these patterns occur, and which deviations might result in system dysfunctions or pathologies. MP will be used as an experimental framework for collecting synthetic data about modeled ISPs for comparison to empirical data collected from real world systems, opening a new avenue for hypothesis testing for SPT. Knowledge gained through the use of automated modeling tools like MP might contribute to knowledge of why deviations from expectation occur at the fundamental general systems level, what exact impacts they have, and how they might be corrected, especially when modeled in the context of interactions with other systems. Producing more models of many ISPs would allow placing the abstracted model in computer space for artificial systems research [7]. Additional steps would then be taken to integrate other proposed ISPs into an overall SPT-MP meta-model, creating more exploratory executions of ISP behaviors and eventually of ISP interactions, and cataloging the formal

MP models of ISPs. The ultimate goal would be to interconnect a sufficient number of the ISPs to yield a very general model of sustainable systems dynamics at all scales and for many types or classes of systems as well as models of dysfunction that are often encountered in engineering and natural systems.

Another fascinating challenge would be to encode the SPT Linkage Propositions (LPs) that describe behavioral influences of one ISP on any other or between many ISPs [49]. This activity would be expected to challenge and yield strong benefits or expansions of understanding of both SPT and MP. For example, how could one encode LPs (perhaps the most creative and original contribution of SPT) in MP models, given that it itself explores behavioral alternatives? How would MP handle hundreds of LPs? Would such MP SPT systems models then more adequately approach or explore such conundrums as "complexity" and "emergence" which are of great interest to both systems engineers and systems scientists?

Beyond the LP extension of individual ISP MP models, future work could include using MP to explore another line of research spun off from SPT, namely, Systems Pathology. MP has already demonstrated its ability to expose the negative aspects of a process, i.e., how systems don't work or dysfunction [27,39]. Once the alternative behaviors of an ISP are modeled, MP could be used to eliminate some of the behaviors, constraints, or LPs and assess how this changed or caused dysfunction in the normal operation of an ISP in various and changing environments and contexts.

MP provides a virtual systems laboratory for reasoning about the behaviors of systems based on a series of events that unfold given the presence or absence of linkages or dependencies. MP may be used in the future to support or refute various claims made about cycles and other ISPs, leveraging the formality it brings to the description of ISPs and their various manifestations.

Author Contributions: K.G. wrote the MP models, performed the experiments, and contributed the descriptions of the MP framework to the paper. L.T. provided the source data for the models, contributed the descriptions of the SPT, and documented the implications. Both K.G. and L.T. wrote the Introduction, Conclusions, and Future Work.

Conflicts of Interest: The authors declare no conflicts of interest. No sponsor had a role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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Using Systems Thinking to Understand and Enlarge Mental Models: Helping the Transition to a Sustainable World

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Received: 1 March 2018; Accepted: 3 May 2018; Published: 8 May 2018

Abstract: Sustainability and climate change are massive global problems that stem from the industrial world's relentless pursuit of growth. Transitioning to a sustainable world requires understanding citizen mental models and our addiction to short-term rewards. This paper uses causal loop diagramming (CLD) to describe the general, prevailing citizen viewpoint and to propose a wider mental model that takes the natural world and sustainability into account. The corporate profit model that depicts the wider view acknowledges and describes the important impacts and influences of political pressure on our social, economic, and ecological systems. Adopting the wider mental model can help the industrialized world design better policy to achieve both national and United Nations (UN) sustainable development goals.

Keywords: sustainability; systems thinking; UN sustainable development goals; mental models; neoliberalism; ecological economics

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1. Introduction: The Nature of the Sustainability Problem

In 1972, a team from the Massachusetts Institute of Technology (MIT) developed a world (computer) model and published a report to the Club of Rome, titled the "Limits to Growth" [1]. The report linked the world economic system with the state of our natural world. The main message from the report is that economic growth and material consumption cannot continue infinitely on a finite planet.

The world model was initially heavily criticized since it conflicted with the growth mindset and predominant worldview. A number of criticisms falsely claimed that the model predicted resource depletion and world collapse by the end of the 20th century. "Limits to Growth" did not make that claim. However, a recent empirical study did find that actual data very closely follow the "standard run" scenario of the world model and that we are in fact on an unsustainable trajectory unless there is substantial and rapid reduction in consumption coupled with technological progress [2].

Environmental Impacts

Environmental impact is defined as increases in use of resources (renewable and non-renewable) and degradation of the environment (land, water, air, and resources). The classic IPAT formula defines environmental impact as arising from the interaction of 3 major factors [3,4]:

$$I = P \times A \times T \text{ (IPAT)} \quad (1)$$

where I = environmental impact, P = population, A = affluence, and T = technology.

The use of the IPAT formula typically involves examining a specific impact, such as resource use (e.g., oil), from a source, with affluence represented by gross domestic product (GDP):

$$I = P\ (\cancel{people}) \times A\ (\cancel{GDP}/\cancel{people}) \times T\ (\text{billions of barrels}/\cancel{GDP}) \quad (2)$$

With resulting impact in terms of billions of barrels used [5].

Alternatively, another specific impact could be the result of human activity, i.e., dumping a waste or by-product into an environmental sink, such as CO_2 output to be absorbed by various sinks (ocean, atmosphere, rainforest):

$$I = P\ (\cancel{people}) \times A\ (\cancel{GDP}/\cancel{people}) \times T\ (10^6 \text{ metric tons } CO_2/\cancel{GDP}) \quad (3)$$

With resulting impact in terms of 10^6 metric tons CO_2 produced [5].

In both cases, i.e., excessive CO_2 output to the atmosphere (sink) or excessive use of resources like oil (source), the human system is generating these problems because of exponential growth in affluence (GDP) and population [1].

These environmental impacts contribute to unsustainability. Sustainability means (1) achieving reasonable rates of usage for renewable resources, such as fisheries or timber, that are less than or equal to their natural regeneration; (2) pollution, garbage, and byproducts of consumption cannot be generated faster than they can decay and be broken-down into harmless components; and (3) in the long-run, we cannot use non-renewables at all [6,7]. Therefore, the IPAT formula serves as a useful framework for understanding sustainability and/or areas where our world is unsustainable.

Unfortunately, as the poor nations of the world struggle with population growth and trying to increase their economic output to help reduce poverty, the rich nations continue to use too many resources in an effort to satisfy competitive consumption and excessive wants [8]. Meanwhile, political systems attempt to satisfy citizens' consumption needs by pushing for more economic growth. It's a political-economic system driven by short-term rewards for politicians, citizens, and corporations [5]. The ability to achieve a global balance in the system does not appear to be easy.

2. The United Nations (UN) and the Sustainable Development Goals

The essence of sustainability is to "live within our means", and global sustainability refers to living within the limits of a finite planet. The concept of sustainable development first became popularized in the 1987 report of the World Commission on Environment and Development, Our Common Future [9]. The report reinforced the "Limits to Growth" and again brought into public consciousness a crucial concern—that global economic growth must be reconciled with the reality of limited natural resources and the dangers of environmental degradation. The report defined sustainable development as:

> ... *Development that meets the needs of the present without compromising the ability of future generations to meet their own needs* [9].

Implicit within the 1987 UN statement is the distinction between "the needs of the present" (a short-run focus) and "without compromising the abilities of future generations" (a long-run focus). This is an important distinction because of the fundamental worse-before-better (or better-before-worse) system property that "a policy that seems better in the short run is almost always worse in the long run" [10] (p. 365). Examples of this system property include normal business investments that increase short-run expenses but lead to long-run profit, or conservative quota policy in fisheries that restricts the catch and profit in the short run, allowing the fish stock to build back up and eventually leading to better long-run profit [11]. In essence, good policy aimed at long-run outcomes generally requires some short-run sacrifice.

Since 1987, many corporations, non-governmental organizations (NGOs) and governments have set sustainability goals, but global progress on sustainability has been limited. On 25 September 2015 the United Nations adopted a set of sustainable development goals (see [12]). The sustainable development agenda aims to end poverty, protect the planet, and ensure prosperity for all (equality). Unfortunately, as the world currently operates, these goals are almost certainly conflicting.

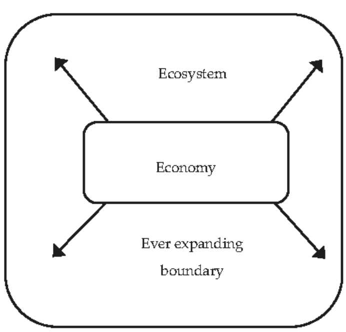
3. Mental Models

Inadequate mental models have contributed to the structure of our current system, where government has adopted the conflicting goals of: (1) protecting the common good and rights of individuals, and (2) seeking to create employment security and reduced poverty through promoting economic growth [13]. However, as shown in the IPAT formula, increases in GDP through economic growth produce many environmental impacts and depletion of resources, both of which harm future generations. In addition, promotion of economic growth typically comes through policies that reduce corporate taxes and relax government regulations, and these policies often have the adverse effect of increasing wealth disparity [14].

Mental models are cognitive representations of external reality. The notion of a mental model was originally postulated by the psychologist Kenneth Craik [15], who proposed that people carry in their minds a small-scale model of how the world works. These models are used to anticipate events, reason, and form explanations [16].

When examining global sustainability and climate change, mental models of economic variables are of particular importance. The number of variables considered and the boundary of the mental models used in the economic domain depend on one's world view. One view provided by many standard economic textbooks shows the circular flow of the economy as a closed system where interactions with the natural world are largely ignored [17]. This naturally leads to a restricted mental model; one that does not consider environmental limits.

This closed world view promotes the following ideas: resource extraction can continue indefinitely, and if any resources do become scarce, then the free market will simply use technology and substitution to allow economic growth to continue [18]. Figure 1 compares and contrasts the traditional economic model, economic imperialism (1A), with the ecological economics or steady-state subsystem (1B). In Figure 1a (economic imperialism), the arrows represent the idea that the economic subsystem can expand until it encompasses the whole ecosystem. In this view, the entire system is conceptualized as the macro-economy, including the ecosystem. Everything in the ecosystem is theoretically considered comparable in terms of its ability to help or hinder people in satisfying their wants [17]. Economic imperialism assumes that everything can be priced, and that subjective, individual preferences are taken as the source of all value. Since subjective wants are thought to be infinite in the aggregate, there is the assumption that the economy will grow infinitely in order to satisfy consumers. Such a view promotes the mental model that only economics and economic variables are important. Anthropocentric orientations are focused on human welfare and view the ecological environment as important, but only to the extent that the environment is directly helpful to human needs [19].



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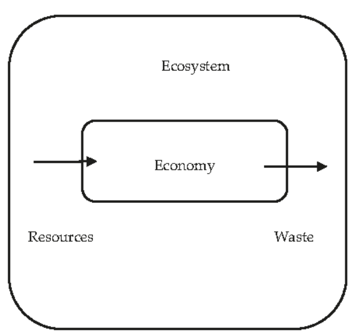


(**b**)

Figure 1. Economic Imperialism versus Steady State Mental Models: (**a**) Economic Imperialism Mental Model; (**b**) Steady State Mental Model.

In contrast, the field of ecological economics is based on the steady-state sub-system view of the human economy. Here, the economy is an open system that exchanges energy and matter with the Earth's ecosystem. The size of the human economy does have some optimal level determined by global society and the ecosystem. In the long run, the human economy must be ecologically sustainable by having the ecosystem maintain and replenish the economic subsystem [17]. A mental model based on this viewpoint naturally incorporates a wider boundary where ecosystem health must be considered with the human economy. The eco-centric orientation argues that nature has an intrinsic value, or a value independent of human interests. This viewpoint is consistent with the environmental sustainability requirement that the integrity of ecosystems be maintained. In essence, this is a long-run and holistic viewpoint as compared with the anthropocentric orientation.

The next section introduces systems thinking as an additional framework that can be used to provide insight into our mental models and to provide an enhanced understanding of the socio-economic variables involved with global sustainability.

4. Systems Thinking and Mental Models: Frameworks to Understand Unsustainability

4.1. Systems Thinking, Interconnection and Focus

Systems thinking tools help us to see the bigger picture and to enlarge our mental models. Enlarging the boundaries of our mental models is critical since decision-making often involves impacts that alter the decision-making environment and ultimately feedback to influence the current situation [20]. Alternatively, if we were to reduce the boundary of the system, we would not eliminate the interconnections that are found in reality. Not recognizing these interconnections in our mental models is a problem causing us to ignore important feedback. This typically leads to decisions that produce "unintended consequences" [20,21].

A more useful and truer picture of our complex systems will show the feedback structure involved. Although systems may involve many hundreds of variables or components variously interconnected, the long-run dynamic behavior of complex systems is generated by the interaction of just two basic types of feedback loops, either reinforcing feedback that increases or amplifies changes, or balancing feedback loops that counteract or oppose change [20]. Appendix A provides an overview of both reinforcing and balancing feedback loops, along with the corresponding causal loop diagrams and behavior-over-time graphs.

When considering the UN Sustainable Development Goals of (1) ending poverty, (2) protecting the planet, and (3) ensuring prosperity for all, we encounter head-on the divergent mental models and world views. The current conventional wisdom is that we need more economic growth to end poverty, produce a larger economic pie to ensure prosperity for all, and to produce the technology necessary to protect the planet [13,18]. On the other hand, the opposite view was concluded from "Limits to Growth," that in fact, economic growth is the cause of these world problems [1,14]. Recent empirical evidence further supports this view that economic growth is the major underlying problem, that economic growth has not been decoupled from consumption-based emissions, but is instead further contributing to climate change [22].

Additionally, although technology can improve resource efficiency, when viewed in a wider context, efficiency gains are often negated by increases in consumption behavior, known as the rebound effect [23].

While technology is indeed necessary to slow the pace of environmental destruction and climate change, the Limits to Growth World 3 model revealed that no set of purely technical changes in any of the computer runs was sufficient to bring about a desirable future. Restructuring social, economic, and political systems was much more effective [14].

4.2. Interconnection and Focus Based on Economic Imperialism

It is impossible to uncover the separate mental models of the millions of individual citizen decision-makers. However, we can narrow our focus to the economic imperialism viewpoint and then examine a subset of important economic variables and their interconnections (Figure 2). In this way, we can then make a comparison with the expanded view based on ecological economics and sustainability.

The bold-faced arrows in Figure 2 show a very narrow and focused view of our socio-economic world and one that we believe a citizen majority use to reason and vote for political leaders. We can state this with a rather high rate of confidence as a majority of political debates and campaigning in the US are centered on jobs and the economy. Climate change and sustainability are virtually never mentioned [24].

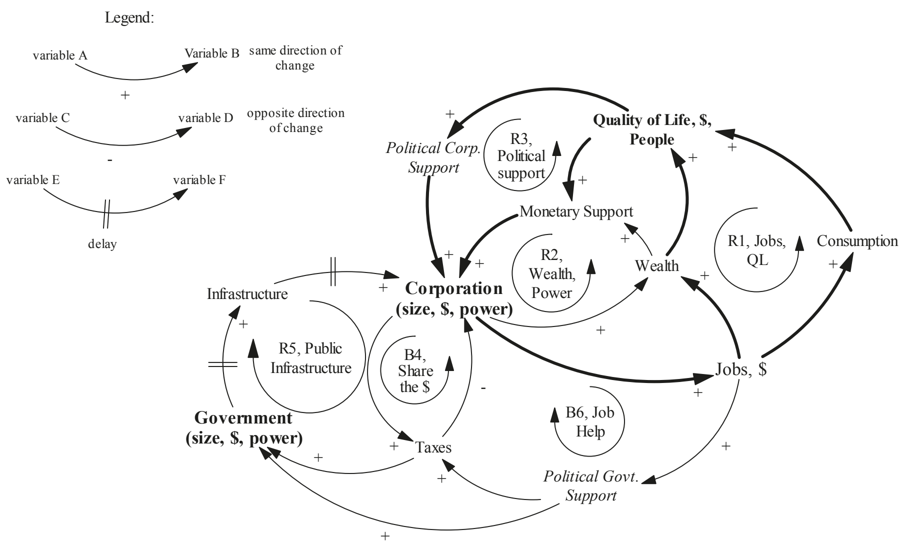


Figure 2. The Prevailing View of Citizens, Jobs and Corporations.

Reading the diagram from the center, as corporations gain size, money and power, this leads to an increase in jobs. The increase in jobs (employment) leads to increases in both consumption and wealth. Increases in consumption and wealth together increase quality of life, as implicitly measured by monetary increases (GDP), ownership increases, and chosen experiences. People then invest money and provide political support for corporations as well. This creates a reinforcing feedback loop that dominates and reinforces our mental models, supporting large companies and the private sector creates growth, jobs, and a higher quality of life for all.

Increases in corporate sector profit will lead to increased tax revenues, loop B4, allowing government to build up infrastructure, which again supports the corporate or private sector. Bold-faced arrows indicate loop dominance. Should job creation be weakened, then a decrease in jobs leads to a decrease in political government support, which then leads to a decrease in taxes and then to an increase in corporations (size, money, power). B6, job help, is a balancing loop, which can counteract any reductions in the ability to reinforce job growth.

Citizen political support is separated into two categories in the model: political corporate support and political government support. Political corporate support represents citizen support for policies that benefit corporations and private sector business. Political government support is citizen support for policies that increase taxes and support for government services and regulation. If citizens are primarily concerned with jobs, political corporate support should dominate political government support and the corporation (size, money, power) variable should increase relative to government (size, $, power).

Reinforcing loops have a tendency to create exponential growth if left unchecked. The bold-faced, dominant loops in the model indicate an increase in support for corporations and the private sector. If taxes are sufficient from corporate profits, then long-run infrastructure support can help to keep the corporation (size, money, power) variable supporting jobs, consumption, and wealth. However, Figure 2 provides a restricted view of socio-economic variables, and one that does not take into account a wider impact on the natural environment or people.

4.3. The Scarcity Mindset, Focus and Tunnel Vision

In a simple sense, a gap between a desired resource amount and the actual resource level can be considered a problem of scarcity. In this sense, scarcity is a physical constraint. But, scarcity is also a broader concept. A scarcity situation invokes a mental state that captures our attention [25]. When individuals are in a scarcity mindset, they become more attentive, focused, and efficient. In a scarcity situation, whether it is a tight deadline (time scarcity) or a cash shortage, we fall into a scarcity mindset because the situation is important and demands our attention. We realize a short-term benefit from this mental state and perform better on our most pressing concerns. However, a hidden downside to the scarcity mindset is that it also causes us to ignore information outside the tunnel and to neglect other issues [25].

In the case of the prevailing view of citizens (Figure 2), mental models are directed at growing the economy and creating jobs. This is such an important consideration that it captures people's attention and helps to drive the R1, R2, and R3 reinforcing feedback loops and increase corporate influence in the economy. Unfortunately, this is an incomplete, narrow, and short-sighted view.

Figure 3 introduces an expanded view that incorporates impacts on our ecosystem and people, the corporate profit loop. The corporate profit loop shows where our current mental models are dominant (bold-faced loops) and it reveals our shortcomings. In order to transition to a sustainable world, we need to move citizens toward a deeper understanding of how our socio-economic system impacts our wider environment.

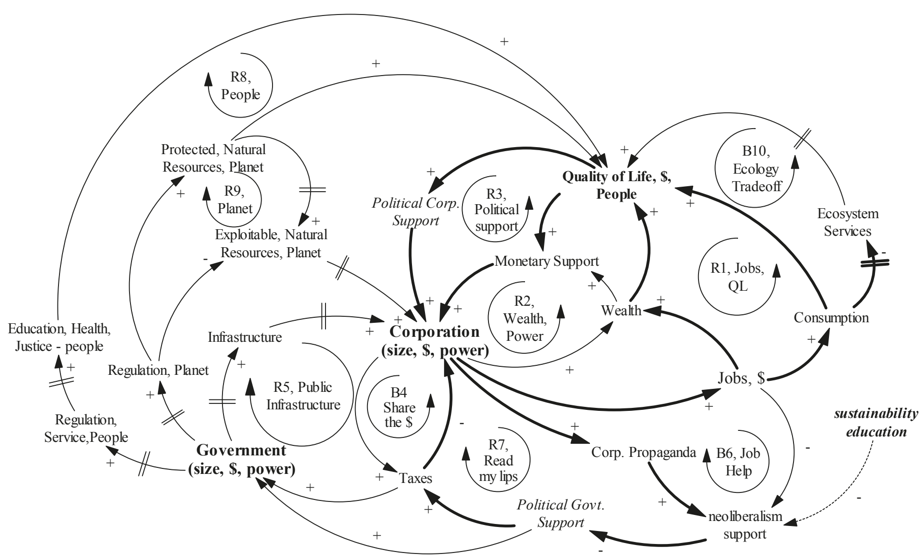


Figure 3. Jobs, Corporations and Power: The Corporate Profit Loop.

5. Expanding Citizen Mental Models: The Corporate Profit Loop

Figure 3 shows the corporate profit loop model, which represents a preferred view and mental model in order to produce a more sustainable world. The corporate profit loop model depicts the interplay between government (size, money, and power) and corporations (size, money, and power). The causal loop diagram represents most of the important known causal impacts involved in this system, but it is important to stress that although a link may indicate causality, it does not indicate what will necessarily happen in such a complex system (Note: dominant links are again shown boldfaced; and the dotted line from sustainability education shows a preferred leverage point). That is, certain causal links may be strong at one time, but weaker at another. Which causal links become dominant depends on both what has happened in the past (i.e., path dependence) and also on what individuals in the system decide to do in the present. That is, social systems are highly dependent on various decisions of individuals within the system.

The "corporate profit loop" model incorporates sustainability thinking, as the three pillars of sustainability are represented throughout, especially: people (as seen in R8, "people" variable), profit (implicitly represented in loops R1 and R2), and planet (R9 and B10).

Another important aspect of the "corporate profit loop" model is that the left portion of the diagram, reinforcing loops R5, R8, and R9, all follow from the public "government size, power, $ variable" and all contain delays. For example, government investment in infrastructure takes time to actually build up roads, bridges, airports, and investments in education, and R&D take time to produce an educated workforce and new knowledge that can lead to improved technologies. Similarly, government can act to protect natural resources, and this can eventually have long-run positive impact on companies (loop R9). For example, fisheries are managed, and stocks remain healthy to produce long-run food supply and jobs. Additionally, non-renewable resources can be used in the short-run to drive economic growth, or they can be conserved (loop R9), for future availability. Government investment is also used to support people directly, through the "Education, Health, Justice-people" variable and R8 People loop. This variable is used to broadly denote the work of government to promote the physical (health care) and financial health of citizens (transfer payments). Obviously, not all details of government can be shown, but the major benefits are summarized. The costs are shown in the form of taxes and represent the costs to the private sector, loop B4.

Delays in the model are significant because outcomes are not achieved quickly, and instead, causal forces may unfold quietly over time and significantly impact long-run behavior.

Naturally, the model can also operate with the left-hand portion dominating. In this case, taxes can be overwhelming and can stifle corporations. This is a dangerous condition because the free market drives employment, wealth creation, and quality of life (as measured by GDP). In addition, as consumption is reduced and corporations lose profits, tax inflows are reduced, which also weakens government and further reduces quality of life. This can behave as a vicious reinforcing feedback loop as lower levels of employment also lead to further citizen dependence on a weakened government.

Reflecting the current citizen mental models, the bold-faced loops in the right section of Figure 3 are shown dominant because of short-termism behavior. Corporations must generate profits and increase shareholder wealth and this puts great pressure on short-term financial results.

5.1. Neoliberalism

Given the almost universal appeal for economic growth and citizen expectations that government should support job creation, reduce poverty and provide more public services, it is not surprising that the pro-growth, neoliberalism ideology has become more widely adopted by governments and policy makers. Neoliberalism is an ideology that strongly emphasizes economic growth as the single most important objective while depicting government as an obstructive force impeding the free market [26–28]. Specifically, neoliberalism supports many policy measures to promote the free market, including massive tax cuts (especially for businesses and high-income earners); reduction of social services and welfare programs, downsizing government, anti-unionization measures, removal of controls of global financial and trade flows, and the creation of new political institutions, think tanks, and practices designed to reproduce the neoliberal paradigm, among others [28]. The variable neoliberalism support is shown as a significant leverage point in the Corporate Profit Loop model and it represents the degree of support for this paradigm. Higher neoliberalism in the model leads to less government support, lower taxes, higher corporate propaganda (promotion of the neoliberalism paradigm), and higher corporate power, and thus, increased job support.

The corporate profit loop model illustrates that as corporations become more powerful, they reinforce neoliberalism and citizen mental models through propaganda efforts that contribute to the growth mindset. Corporate influence can be dangerous because political leaders will feel compelled to support policy that favors short-run corporate interests. Further, citizen support adds to the likelihood that government policy will be aimed at short-run business concerns over the common good.

5.2. The Anthropocene: A New World Created from Human Values, Viewpoints and Narrow Focus

Anthropocentric orientations, together with economic imperialism, can be viewed as a positive force that have generated tremendous wealth for human society. However, this wealth has come at a cost. Externalities from the economic imperialism viewpoint have resulted in extreme changes in biodiversity, habitat and biomass loss, and climate change [29]. The changes are so great that many scientists are now referring to these human impacts as a new geological age—the Anthropocene. Of course, people who view humanity as isolated from nature tend to have a very different value system and may hold a completely distinct set of goals and objectives for society from those with an eco-centric orientation.

Human values can thus have a dramatic impact on the objectives and directions chosen by society. An overly narrow focus on economic imperialism, for example, means that citizens place greater emphasis on gross domestic product (GDP) over sustainable development goals such as conservation of the natural world, economic equality, and social justice.

Historical analysis reveals that resources are consistently and inevitably over-exploited primarily because wealth and its pursuit generates political and social power that is used to exploit the resource [30]. This situation is graphically depicted by the imbalance portrayed in the corporate profit loop and the dominance of feedback that reinforces corporate size, money and power. The further this growth mindset plays out in the global scene as competition among countries, the more industries move to locations with lower cost structures. In essence, we get a standards-lowering competition with increasingly lower labor and environmental regulation [5,6]. Lower costs mean the ability to price lower and further drive growth. More growth, especially in physical products, further drives unsustainability.

The power of global corporations and neoliberalism has created a power imbalance in the world, allowing tremendous bargaining power to corporations, enabling lower cost production for industrialized countries while not necessarily helping poorer countries rise out of poverty [31]. The term neocolonialism has evolved to describe the economic power imbalance [32]. Neocolonialism is also in obvious direct conflict with the UN sustainable development goals.

Poverty in the developing world creates additional problems for sustainability. Indigenous farmers in the developing world often slash and burn rain forest and prime habitat in order to increase their acreage and boost income [33]. Meanwhile, large multi-national corporations such as Monsanto, Dupont, Syngenta, BASF and Dow promote industrial, mono-culture farming practices. The stated idea is to increase agricultural productivity in an effort to help with world hunger. However, such practices require increases in pesticides, herbicides, fertilizer, and water. Adopting these techniques in the developing world is expensive for farmers, who must purchase genetically engineered seeds and additional fertilizer while profits return to the large corporations [34].

The long-run prospects for industrial agriculture are also loaded with risk. Climate change makes farming far riskier as it increases the likelihood of extreme weather along with the potential for pest damage. A far simpler way to handle adverse conditions is to use traditional farming methods.

Agro-ecological farming uses traditional seed and diverse crops for resilience and climate adaptation. This approach has added benefits such as reduced pollution (less fertilizer), reduced costs, and fewer side effects, such as pesticide poisoning of bees and beneficial insects [34,35].

5.3. Lock-In and Deadlock

We cannot expect the free market to develop products and services fast enough to solve our global environmental problems and especially climate change [36]. The primary reason for this is short-termism on the part of citizens, politicians, shareholders, and business owners—all of us. Short-termism can be thought of as a built-in part of capitalism. Specifically, most firms are not in a position to postpone short-term profitability for higher, but time-delayed profits later. Only the government can afford to make many of the larger, riskier and time-delayed investments necessary to combat climate change [36].

Thus, neoliberalism has emerged as an ideology at direct odds with global sustainability and climate change [26,27]. Figure 4 depicts the situation where consumers in the market economy are unable to purchase "green products" due to deadlock or lock-in.

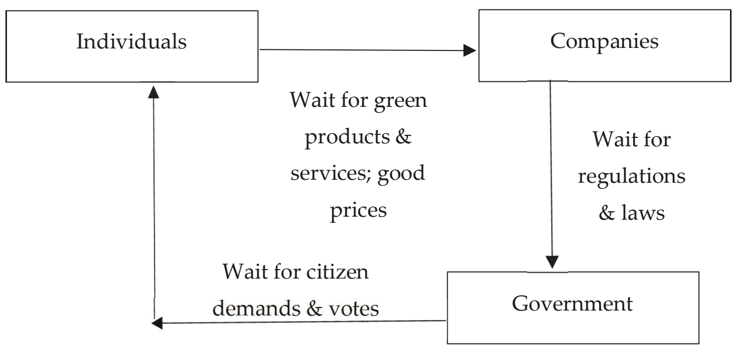


Figure 4. Lock-in and Deadlock: Actors in the Global Sustainability System Exhibiting Diffused Responsibility.

Lock-in occurs in the following way: companies are reluctant to produce green products (e.g., electric or hybrid cars, solar panels) without sufficient demand from consumers. Consumers are reluctant to buy green products because the prices are too high; but prices are too high because production volume is insufficient, a vicious loop [5]. Cutting-edge companies look to government to initiate regulation, but government will not act in democratic societies without substantial support from the public, and legislation that hinders one group will be resisted, even if it benefits the majority [36]. Ultimately, responsibility lies with us—citizens, voters, consumers, and employees. However, realizing the wider system view brings to light the especially important role for citizens/voters in democratic societies, and this is where our deadlock really resides.

Finally, just as the lack of environmental regulation causes a lock-in effect with status quo products, the inability to correctly price energy and incorporate a carbon tax can also be directly linked to citizen votes. Once again, neoliberalism ideology and propaganda influence citizen mental models. Political interference means information feedback (via price signals) is lost as social costs are not incorporated into energy prices. In essence, stressing the free market and economic growth as the answer to our problems causes traditional economic corrections to be rendered ineffective.

The way out of this trap is to first see that we are in an addictive cycle. The Corporate Profit Loop is another portrayal of "the loop you can't get out of" [5,37]. A basic problem is that we are all enticed by immediate rewards (short-run results) and most of our systems are predicated on short-run feedback, including the stock market, quarterly profits, political elections, and consumerism (pursuit of novelty). Once we start down this path (the right-hand side of Figure 3), the system rewards corporations with more money and power to influence the political system and consumer society. Corporate propaganda drives ideological support for neoliberalism. Since corporations influence the political system, neoliberalism creates a reinforcing feedback loop. The more this dynamic operates, the more influential corporations become relative to government. The underlying problem is that the real, physical world does not operate under an economic imperialism model, but we do have limits within a finite planet, and it is becoming increasingly clear that we are living beyond our means and outside of the safe operating space for humanity [2,29]. Eventually, resources become eroded (See Figure 3; R9, Planet Loop) and the balancing loop, B10 Ecology Tradeoff, will also become dominant. Finally, ecosystem services and environmental degradation will reduce our quality of life.

6. Competitive Strategy and Making the Transition to Sustainability

Currently, our mental models remain fixated on the dominant loops in the right-hand portion of the Corporate Profit Loop. This is a dangerous position as corporations have tremendous power to influence government policy and to promote short-termism. Rather than realizing the necessity to transition to renewable energy, policy is used to favor status-quo companies and to keep fossil fuel subsidized. Not realizing or accepting that disruptive technologies are coming does frequently happen in the private sector (e.g., with Eastman Kodak and digital photography [38]). When this occurs in the private sector, it is largely due to the management dogma of listening to customers and shareholders, that is, focusing on short-run concerns [39]. Disruption in the private sector is limited. However, when it occurs on a grand scale, such as with a country's energy supply, the economic impacts can be substantial. Currently, China has plans to invest $360 billion dollars in renewable energy by 2020 [40]. Furthermore, Germany is getting one third of their energy needs right now through renewables [41]. The United States energy policy could thus be putting US companies and the economy at a substantial disadvantage. First-mover advantages can be extremely beneficial for green technologies and products because of learning curve effects [42] (p. 215) and the typically large initial investments required. This is where balancing the Corporate Profit Loop can be beneficial to the economy while simultaneously advancing green initiatives and helping to achieve the UN Sustainable Development goals. Making this happen, however, requires citizen buy-in to break the current deadlock or lock-in.

Unlocking the Freedom of Markets and Government with Systems Thinking and Ecological Regulation

The current world view of US citizens is focused on the high volume, neoliberalism of the right-hand side of the corporate profit loop. While reduced regulation by outsourcing production has helped to keep costs low in the past, this approach is dependent on global consumer and citizen thinking. This is changing. That is, as people's thinking evolves to a "greener" mindset more and more of the global market will be dominated by renewable energy, green products, and innovative services. We know this will happen because we know we are pushing up against more limits. The sooner industrialized countries adopt more stringent environmental and labor regulations, the faster cutting-edge companies can plan, invest, and support innovations [43]. Designing products and services for the strictest regulations will actually streamline manufacturing and logistics and save costs because multiple product versions will not be necessary for international markets [43]. Thus, regulations and economic nudges will be critical to help develop new disruptive technology.

Newer market-based incentives hold great promise for providing the right environment for environmental innovations and technologies [44]. First, a broad natural capital depletion tax could be used to ensure that resource use is sustainable while also providing incentives for new technology development (applicable to Loop R9, Planet in Figure 3). Second, the adoption of a flexible environmental assurance bonding system can be used; this is where an estimate of the largest potential environmental damage is used to purchase a bond, kept in an interest-bearing escrow account, to offset the potential of a catastrophic future effect. This approach is consistent with the precautionary principle, and it requires committing resources in the present. Again, such an approach would encourage technology innovation as the burden of proof, and cost of uncertainty is shifted from the public to the resource user (applicable to Loop B10, Ecology Tradeoff in Figure 3). Finally, the use of ecological tariffs could be used to “level the playing field” for those countries that do not adopt these market-based incentives. In fact, given recent global commitments and UN sustainable development goals, such ecological tariffs could be politically possible [44] (pp. 247–256).

Therefore, sustainability education is vitally important because it can inform citizens who must vote and pressure policy makers to create the most responsible business climate for sustainable innovation. Sustainability issues are extremely complex because they are embedded in a global web of systems, political processes and dynamic interactions [45]. Systems education is a necessary and ideal complement to sustainability because tools like stock-and-flow diagramming and computer simulation can contribute to a better understanding of sustainable business and socio-economic-political systems.

Over-focus on only one part of the corporate profit loop can lead to excessive exploitation of people and planet. This narrow range of concern or focus can be rationalized, but this type of rationalization can more accurately be portrayed as bounded rationality. Liberal arts education that opens minds to concerns beyond short-term profits and economics can be beneficial. Rationality that is more open to different views, cultures, feminism, and the natural world can develop a more just and equal society [46]. In fact, the rationality and value system that focuses on and seeks endless economic growth is at the heart of our multiple crises of ecological destruction; economic, gender, and racial inequality; and poverty [47,48]. Indeed, corporations that can open up from just a shareholder profitability perspective to a wider concern for all stakeholders will have reduced risks and better prospects for sustained profits [49]. A sustainable world requires an equitable distribution of wealth and resources [33]. We cannot expect the poor in the developing world to go without food, nor can we expect the poor in industrialized countries to be able to afford green products and energy while the rich use up excessive resources.

Education that opens citizens’ mental models and expands the boundary of their thinking will help to reveal important feedbacks and long-run dynamic behavior. The corporate profit loop model is a fairly concise and simple model that reveals where our current citizen mental models fall short. Sustainability education, coupled with systems thinking and system dynamics, can inform citizens and help us rebalance the corporate profit loop.

7. Conclusions

This paper has proposed the corporate profit model as an expanded view of the important variables from the economic, social, political, and ecological systems that interact with and impact our ability to achieve a sustainable world. In particular, corporate power is shown to be a primary cause of political influence, policy formation, and perpetuation of neoliberalism. Corporations have often co-opted or appropriated the language of environmental citizenship and have positioned themselves as ideal environmental citizens, all the while driving their companies and customers to be unsustainable over-consumers [50].

Enhancing citizen mental models is necessary for the implementation of good public policy and market-based incentives to promote global sustainability. Moving citizen understanding from narrow conceptions of the economy to a wider view is an essential first step. Fortunately, ecological-economic precautionary policy instruments exist and show promise to halt our ecological crises.

Neoliberalism and excessive focus on economic growth are actually hindering both our long-run prosperity and our ability to make progress on the UN Sustainable Development Goals. Our system of defining public policy has deep flaws. Our policies are based on short-run pressures that inevitably produce long-run failure [10]. Pushing economic growth, especially using neoliberalism tactics, is a short-run strategy. Complex non-linear feedback systems exhibit better-before-worse dynamics [10]. In the long-run, our market economy will inevitably become more focused on green products and technology, especially renewable energy. This is because we are increasingly pushing up against ecological or planetary limits. Pushing for more economic growth using neoliberalism actually hinders our economy in two ways: (1) Over consumption of material goods produced with fossil fuel energy harms our ecosystems and is beginning to cost the economy more than the benefits we receive [6] (see Figure 3, B9, Ecology Tradeoff); and (2) the neoliberalism focus on the right-hand side of the Corporate Profit Loop is a reinforcing feedback loop, and it diminishes the ability of government to protect our long-run, common good interests (e.g., protecting and conserving natural resources, maintaining and building infrastructure, initiating sustainable business support and protecting the rights of individuals).

Corporations influence much of the public policy formation in the US democratic system. Powerful lobbying is largely a function of money and resources, and US corporations are able to have their voices or free speech heard. Although long-run policy issues like global sustainability and climate change are important for the general public, large corporations that are tied to the fossil fuel economy are making more profits now by focusing on short-run concerns.

The ability to increase our quality of life, reduce our environmental impacts, reduce poverty, and increase economic equality all require restoring a balance in the Corporate Profit Loop.

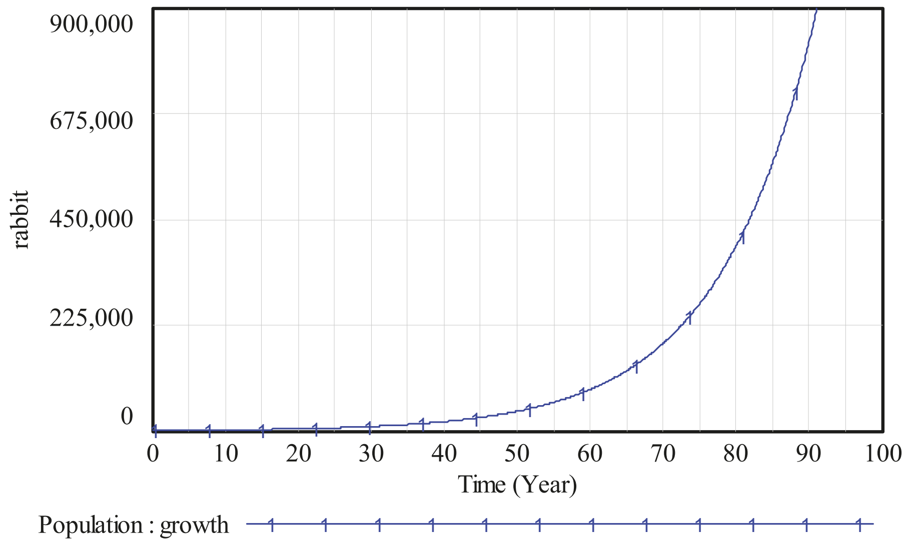
Funding: This work is funded through Canisius College.

Conflicts of Interest: The author declares no conflict of interest.

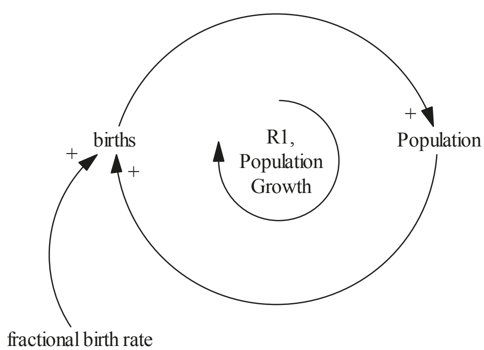
Appendix A. Understanding Reinforcing and Balancing Feedback Loops

A behavior over time graph and a causal loop diagram (CLD) of reinforcing feedback are shown in Figure A1. A reinforcing feedback relationship produces an exponential growth pattern. The causal loop diagram illustrates that a *higher* amount of births leads to a *higher* population, and a *higher* population (increase) also leads to *higher* births (increase) (i.e., the '+' symbol indicates the same direction of change). Such a graph over time can be generated from all reinforcing feedback loops: for example, the higher the amount on deposit in the savings account will lead to higher interest income that adds to a higher bank balance. Reinforcing feedback loops can also operate to produce a decay pattern over time. If a population is declining due to greater predation, hunting or fishing (or other influences), then a lower population level leads to a lower net birth rate. Thus, a *decrease* in births leads to a *decrease* in the population (i.e., the '+' symbol indicates the same direction of change), which then leads back to a *decrease* in births.

Naturally, rabbits (or any population) do not generate infinite or astronomical population levels, as shown in Figure A1. Eventually limits are reached. In Figure A2, the reinforcing loop, R1, generates rapid growth in the rabbit population in the beginning, but the balancing loops, B2, and B3 and B4, begin to dominate as the population pushes up against the carrying capacity of the environment (note: the | | delay mark between population and resource adequacy in Figure A2, causal loop diagram b; and the '–' symbol indicates the opposite direction of change, so as the population *increases*, the resource adequacy *decreases*. The reverse would also be true: if the population was *decreasing*, then the resource adequacy would be *increasing*). When resources decrease and the balancing feedback loops dominate, we observe the common S-shaped behavior-over-time graph. This pattern is quite common in many natural populations since there are often many limiting factors to place a check on runaway (exponential) population growth.

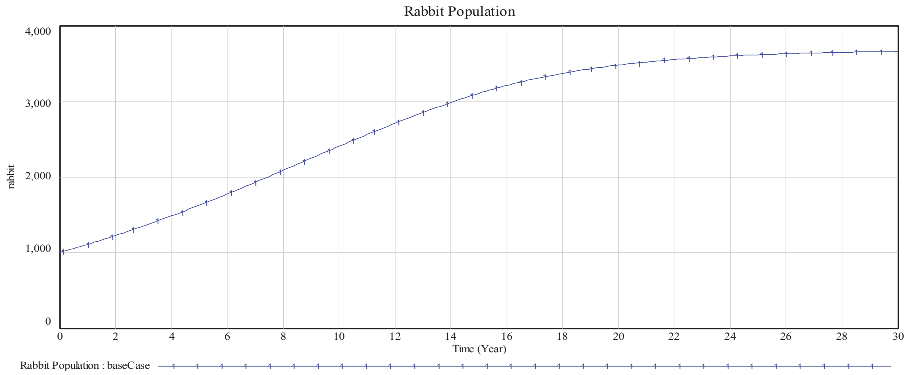


(**a**)



(**b**)

Figure A1. Graph and Causal Loop Diagram of Reinforcing Feedback. (**a**) Rabbit Population Graph, Behavior over Time of Reinforcing Feedback. (**b**) Causal Loop Diagram (CLD) of Reinforcing Feedback.



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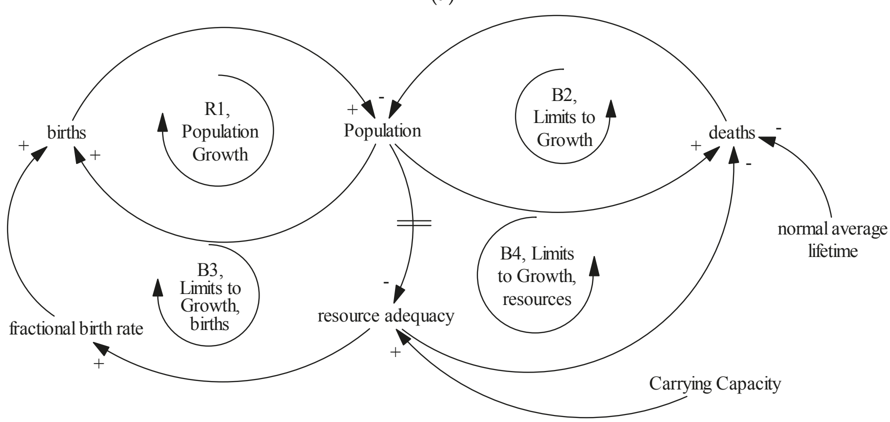

(**b**)

Figure A2. Graph and Causal Loop Diagram of Reinforcing and Balancing Feedback. (**a**) Rabbit Population and Behavior-over-Time Graph. (**b**) Causal Loop Diagram of both Reinforcing and Balancing Feedback, Rabbit Population.

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systems

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Article

On the Architecture of Systemology and the Typology of Its Principles

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Received: 11 February 2018; Accepted: 9 March 2018; Published: 13 March 2018

Abstract: Systems engineering is increasingly challenged by the rising complexity of projects undertaken, resulting in increases in costs, failure rates, and negative unintended consequences. This has resulted in calls for more scientific principles to underpin the methods of systems engineering. In this paper, it is argued that our ability to improve systems Engineering's methods depends on making the principles of systemology, of which systems engineering is a part, more diverse and more scientific. An architecture for systemology is introduced, which shows how the principles of systemology arise from interdependent processes spanning multiple disciplinary fields, and on this basis a typology is introduced, which can be used to classify systems principles and systems methods. This framework, consisting of an architecture and a typology, can be used to survey and classify the principles and methods currently in use in systemology, map vocabularies referring to them, identify key gaps, and expose opportunities for further development. It may, thus, serve as a tool for coordinating collaborative work towards advancing the scope and depth of systemology.

Keywords: systems philosophy; heuristic systems principles; scientific systems principles; general systems principles; specialized systems principles; general systems theory; GST

1. Systemology: Its Rise and Challenges

Over the last few decades the systems paradigm has become ubiquitous in academia and society, and the major fields of academic endeavour (philosophy, science, engineering, and practice) have each developed a nascent systemic specialisation (systems philosophy, systems science, systems engineering, and systems practice). However, the unified systems discipline we would call "systemology" is not yet established as such in academia[1]. The main reason for this lack of coherence is that systems *science* is still very young, and has no unifying general theory of systems. This has left systems engineering and

[1] The term "Systemology" was coined by Russ Ackoff ([1], p. 669), and recently promoted by Pouvreau and Drack as an apt translation of the German term, Systemlehre, meaning "an organized body of knowledge about systems" ([2], pp. 282–283). The term Systemlehre was introduced by Ludwig von Bertalanffy in the 1940s. He translated Systemlehre in 1950 as "Systems Theory" and hence his term Allgemeine Systemlehre as "General System Theory" [3], but this was an unfortunate translation choice, as shown by his proposal in 1972 to describe "General System Theory" as embracing "systems science", "systems technology" and "systems philosophy", ([4] pp. xix–xxiii). The term "Systemology" is now being widely adopted, e.g., [5–8], and "General Systemology" has been proposed as a better translation of von Bertalanffy's term "General System Theory" [2].

systems practice[2] dependent on largely heuristic systems principles. As will be discussed below, the need for fundamental progress in systems science is now acute but, happily, such research is now gaining momentum. To support this contemporary research effort this paper presents an architecture for systemology that can be used to understand how the components of systemology depend on, and reinforce, each other, and on this basis proposes a typology for classifying the principles each inherits or produces. It is hoped that this will inspire collaboration and aid co-ordination across the facets of the systems community, and so help to accelerate scientific progress in the maturation of systemology.

2. The Need for a Stronger Systems Science

The systems we would seek to build, govern or nurture are rapidly rising in complexity, and the associated projects are increasingly prone to underperformance, negative unintended consequences and even outright failure. Major US defence systems projects typically overrun by about 50% [9] and large civil systems projects often overrun by 200% or more [10]. Two thirds of big IT projects fail, and more than half of those that are completed under-deliver on their promised value [11]. The global cost of these failures and shortcomings is very large. In the USA, the cost of systems engineering failures now exceeds $73 billion per annum [12], and the global cost of IT project failures is now estimated at more $3 trillion per annum [13]. Individual projects can fail even after very large investments: a recent US IT system project was abandoned after a spending of $100 million [14], and a recent UK IT system project was abandoned after a spending of £9.8 billion [15].

One response to these challenges has been renewed calls for advances in systems science, to more powerfully support the methods of systems engineering (SE) and systems practice. Such calls have recently been made in many stakeholder organizations, including the National Science Foundation (NSF), the International Council on Systems Engineering (INCOSE), the International Federation for Systems Research (IFSR), and the International Society for the Systems Sciences (ISSS) [16–19].

This call for advances in systems science has triggered renewed interest in systems principles and further calls for enriching the heuristic principles in current practice with more scientific ones. For example INCOSE, in their "Systems Engineering Vision 2025", said:

> "It is therefore important to develop a scientific foundation that helps us to understand the whole rather than just the parts, that focuses on the relationships among the parts and the emergent properties of the whole. This reflects a shift in emphasis from reductionism to holism. Systems Science seeks to provide a common vocabulary (ontology), and general principles explaining the nature of complex systems". [17]

This reiterates an earlier call by Ludwig von Bertalanffy, one of the founders of the ISSS, for the development of a general theory of systems, saying:

> "It seems legitimate to ask for a theory, not of systems of a more or less special kind, but of universal principles applying to systems in general. In this way we come to postulate a new discipline, called General System Theory. Its subject matter is the formulation and derivation of those principles which are valid for 'systems' in general". [20]

These calls have stimulated recent debate about the nature, role and developmental status of systems principles, and this paper is a contribution to that discussion. In particular, I will here

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[2] The term "Systems Practice" refers to a professional activity involving the application of "Systems Thinking" to address a problem or pursue an opportunity, typically (but not necessarily) in the context of management science. Systems Thinking is a form of analysis and synthesis that emphasizes systems concepts such as stakeholder, hierarchy, emergence, feedback and boundary. Systems thinking can enter into any phase of a project, e.g., problem structuring, research, design or intervention, but systems practice is the application of systems thinking for the purposes of staging an intervention. In this way Systems Practice involves the selection, deployment and operation of a systemic solution to a given issue. This may (or might not) involve the use of technological products.

argue that these questions should be addressed in the light of how principles are understood, used and discovered in general, rather than exclusively building on the ideas of the founders of the systems traditions.

3. What Are Systems Principles?

In general, a "principle" is a fundamental idea or rule that can provide guidance for making a judgement or taking action. Principles can take the form of injunctions, beliefs, concepts, assumptions or insights. Principles can range from fully heuristic ones (distilled from experience, intuition, belief or convention) to fully scientific ones (distilled from scientific theories or models). Principles are encountered in every sphere of human activity, so we have, e.g., principles relevant to ethics, aesthetics, economics, politics, science, engineering, agriculture, etc.

Examples of principles include the heuristic principle "do as you would be done by" and the scientific principle that "energy is conserved in all causal interactions". Historically, principles start out as heuristics, and over time some become more scientific, e.g., Lucretius's heuristic principle from 75 BCE that "nothing can come from nothing (or go to nothing)" is today the scientific principle that "energy cannot be created or destroyed but only transferred or transformed". As principles become more scientific, they become more useful for making apt judgements or taking effective action.

By "more scientific" principles we mean principles that more strongly reflect the scientific approach, that is, using clear and precise concepts, expressing qualities and relationships that can be subject to measurement, quantification, empirical verification or falsification, and so on. In this sense scientific principles can arise in philosophy, science, engineering, and operational/service contexts. The scientific enterprise can be viewed as aimed at making principles across these domains increasingly scientific.

Note that we make a distinction between "scientific principles" in the sense just explained and "science principles", i.e., the principles underpinning science.

Both heuristic and scientific principles can be either general (applying universally, e.g., conservation of energy) or specialised (applying only in specific contexts, e.g., the principles of disease prevention), as illustrated in a simplified way in Figure 1 with example principles.

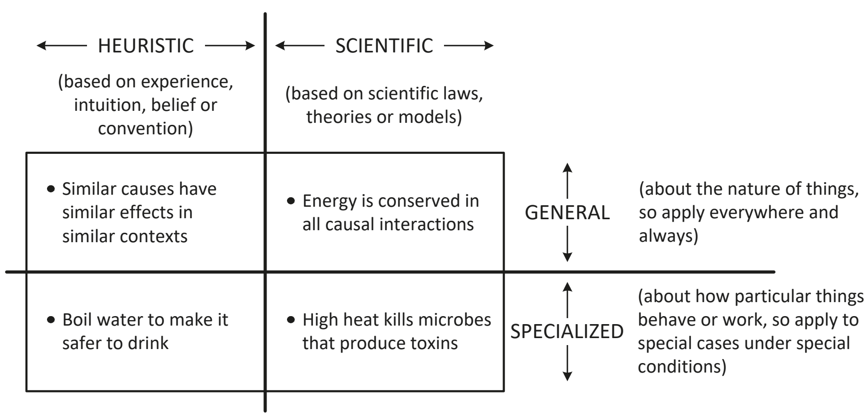

Figure 1. Relationships between forms of principles.

The effectiveness of science depends on having strong principles underpinning scientific research methods at a fundamental level (e.g., the general principles that energy is always conserved or that effects have sufficient causes) enabling scientific activities to discover specialized laws of nature (e.g., Boyle's Law that states the balancing relationship between pressure and volume in an ideal gas) and to reveal strong explanatory principles (e.g., that infections are caused by microbes).

From this understanding of the nature of principles we can now say that *systems* principles are fundamental rules, beliefs, ideas or insights about the nature or workings of systems, and hence systems principles guide judgment and action in systemic contexts. In the case of systems science the search for scientific systems principles (SSPs), and in particular *general* SSPs will be subject to the same considerations that apply to principles in general, as outlined above.

4. Status of Systems Science

The nature and roles of principles as articulated above explains why the calls being made for advances in systems science are framed in terms of establishing more scientific systems principles. Without strong scientific principles reinforcing systems science it cannot be effective in explaining the failures of systemic methods or in uncovering profound insights about the nature and workings of systems.

The present situation is far from ideal. We currently have hundreds of methodologies for systems practice (e.g., SSM, VSM, systems dynamics, CSTP, systemic intervention, etc.) and likewise for systems engineering (e.g., IBM Rational Harmony for SE, OOSEM, JPL-SA, SYSMOD, Vitech MBSEM, etc.), but typically these are only weakly grounded in scientific systems theories. We presently have only a dozen or so scientific systems theories (e.g., control theory, network theory, hierarchy theory, complexity theory, theory of dissipative structures etc.). We have no established general theory of systems, and when it comes to *general* systems principles we have only about a dozen or so heuristic rules (see e.g., ([21], pp. 60–71), ([22], pp. 17–30), ([23], pp. 20–21)[3] and a small handful of general concepts (e.g., wholeness, part, equifinality, closed and open system, etc. (see, e.g., ([31], pp. 91, 95)[4]. These concepts are still far from settled, including even the concept of "system" [39]. Three general scientific systems principles have recently been proposed [40] but they have yet to be formalized, and initial projects to evaluate them are still in process [41].

To fully appreciate the nature and scope of the scientific systems principles we are looking for it is necessary first to consider the nature and scope of system science, with a view to understanding how principles both underpin and flow from systems science, and second to consider how systems science and its principles relate to the other facets of systemology (systems philosophy, systems engineering, and systems practice) and their respective principles.

5. The Nature and Scope of Systems Science

A starting point for thinking about systems science is the view that every concrete thing is a system or part of one, and that natural systems can be arranged into a "complexity hierarchy", in which the "levels" represent increasingly complex systems that embed systems from the "lower" levels, and every level corresponds to some kind of system, as shown in a simplified way in Figure 2. A version of this perspective already occurs in Aristotle, but there is now an extensive modern literature on this, e.g., [42,43], and, notably, in the specific context of general systems theory, a seminal paper by Kenneth Boulding [44].

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3 It should be noted that systemists have published many statements under the rubric of "general systems principles" or "general systems laws" without these statements being actually useful for making judgements or taking action. These typically are just witticisms or platitudes about systems, such as "today's problems come from yesterday's solutions" (Senge), or "complex systems exhibit unexpected behaviour" (Gall). See, e.g., [24–26]. Others have published principles that are useful but not general, notably [27], which lists principles for specific contexts such as architecting, design, social systems, and political processes. For summaries of other specialised principles, see also [28–30].

4 There are very many concepts relevant to systems in the vocabulary of Systemology, e.g., there are 3807 entries in the second edition of Charles Francois' International Encyclopedia of Systems and Cybernetics [32]. These terms are far from standardised, and hence many systemologists have produced their own lists, e.g., [33], ([34], pp. 21–33), ([35], pp. 11–46), [36], ([37], pp. 13–68), ([38], pp. 353–360). However, very few of these concepts are general systems concepts, i.e., concepts describing universal attributes of systems as systems.

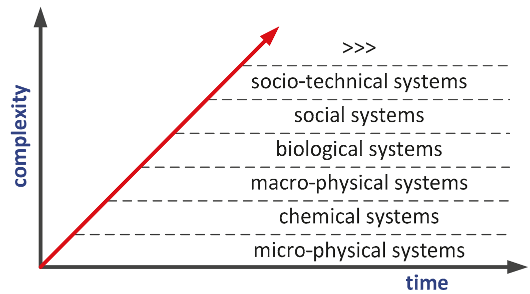

Figure 2. The levels hierarchy and its emergence over time (reproduced from [45], with permission).

The system levels in the complexity hierarchy correspond to the subjects of concern of the mainstream specialised scientific disciplines, so it can be said that every specialised scientific discipline studies some kind of system. Note, however, that this does not make these disciplines systems sciences, since it is only trivially true that their subjects are systems. These specialised disciplines do not have as their subject matter systems *as systems* but, rather, they seek to understand instances of kinds of systems.

The idea of a science of systems arises from three reflections on the complexity hierarchy:

i. First, given that systems occur on every level of the complexity hierarchy, a science of systems must be about what is true of or possible for systems across all the levels. This is the insight behind the claim that system science will be a transdiscipline, having relevance across the disciplinary spectrum, and will comprise theories that are scale-free and composition-independent. At a minimum, such a science must involve concepts and principles that allow systems to be characterised as a category of analysis distinct from things that are not systems, to enable instances of systems to be identified in the real world, and to explain/predict the behaviour and potential of systems as systems. Our present notions of "systemhood" are far from settled, but there is a rich literature on the subject [3,46–49] (see also footnote 3) and important efforts are under way to consolidate these ideas [39,50].
ii. Second, when looking across the levels we find similar patterns recurring across multiple levels, e.g., spiral forms in certain tropical storms, sea shells, flowers, and galaxies. Other examples include Fibonacci sequences and Zipf's Law regularities in natural phenomena [51–53]. Speaking metaphorically, these patterns represent solutions to design problems that systems must solve in order to create enduring complex structures. The existence of these isomorphically-recurring patterns across changes in scale and composition entails that there must be transdisciplinary specialised systems principles reflecting the nature of these "solutions". In principle each of these patterns can be "decoded" to establish a theory that explains the nature and function of the observed pattern, and to identify the relevant explanatory principles. Each such theory would then be a specialised systems science theory, and we have several of these already (e.g., control theory, hierarchy theory, network theory, communication systems theory, theory of dissipative structures, etc.). There are still many patterns in nature we do not theoretically understand, for example patterns of overlapping Fibonacci spirals, and Zipf's Law patterns. Moreover it is likely that there are further patterns we have not yet identified.
iii. Third, the isomorphically-recurring patterns arise independently in multiple contexts involving different scales, compositions, and developmental histories. This suggests that there are general systems principles that provide for the possibility of the *emergence* of these systemic patterns across contexts. Speaking loosely, these would be general principles about how Nature "finds" solutions, rather than (as above) specialised principles about how specific kinds of solutions

work. We have very limited knowledge of such general systems principles[5], but, in principle, they hold the promise of a general theory of systems that would explain both the emergence of specialized patterns and the relationships between them. Such a "general systems theory" (GST) would be very valuable not only for unifying the body of specialised systems knowledge but also for opening up new routes to discovery, just as Mendeleev's periodic table of elements did for Chemistry and Darwin's theory of natural selection did for biology.

From this we can infer that the theoretical aspect of systems science minimally comprises a set of concepts used to characterise the universal attributes of systems as systems, a database of isomorphic systems patterns[6], specialised systems theories that explain the mechanisms underpinning specific isomorphic systems patterns, and a general theory of systems that explain how the universal system attributes arise in nature and how they support the emergence of the isomorphic system patterns. The insights entailed by these concepts and explanations are the general and specialised principles of systems science. In addition systems science also includes the hybrid theories where systems principles are used or derived in the study or modelling of specialised kinds of systems, e.g., systems biology, systems ecology, systems psychology, systems economics, and so on.

We can now paraphrase Figure 1 for the case of *systems* principles, as illustrated in Figure 3. In the light of this four-fold classification system it is evident that that we know some general heuristic systems principles, many specialised heuristic principles, a small but respectable collection of specialised systems principles, and are almost entirely lacking in general scientific systems principles. This pattern of available principles of course reflects both the experiential richness and the theoretical immaturity of our knowledge of systems.

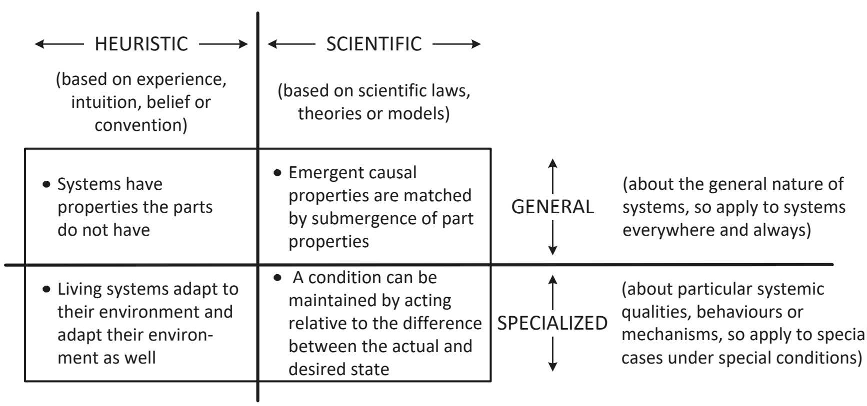

Figure 3. Relationships between forms of systems principles.

As the following discussion will make clear, developing the principles and theories of systems science will require the combined efforts of systems philosophers, systems scientists, systems engineers, and systems practitioners. To explain this, I will start by looking at the general structure of disciplines and disciplinary fields. To keep the presentation concise I will gloss over some nuances and details but, in my view, this does not distort the models being developed, and having been pointed out can

[5] Early work on general systems principles focused largely on general concepts (e.g., ([31], pp. 91, 95)), and while these remain controversial, important progress is now being made (e.g., [39]). In addition, progress is now being made towards establishing propositional general scientific systems principles. Two recent papers respectively presented three such principles [40] and eight strategies for discovery projects [54].

[6] Len Troncale and colleagues have over 40 years made an important contribution to the development of such a database of systemic isomorphisms, and extended this by also analysing the linkages between isomorphisms [51–53,55,56].

safely await elaboration at a later time. Moreover, the focus will be on disciplines that are, or aspire to be, scientific, and I will not here attempt to adequately reflect other kinds of disciplines. However, by focusing on disciplines that are or try to be scientific in their approach we can include consideration of disciplines from various branches of philosophy and practice, in addition to those from ("hard") science and engineering.

6. The General Architecture of Disciplinary Fields

For present purposes I will use the term "scientific endeavour" to refer to the typical activity sequence of disciplines that are or try to be scientific in their approach.

In general we can view scientific endeavours as motivated by some perceived personal or social problem, challenge, concern, opportunity or interest, and aimed at resolving, mitigating or satisficing that issue. The activities that underpin such endeavours come in several kinds, which form a general pattern of stages as illustrated in Figure 4. We can view this as the stages or phases of a typical project. For each of the stages I indicated terms often used to characterize the activities of that stage.

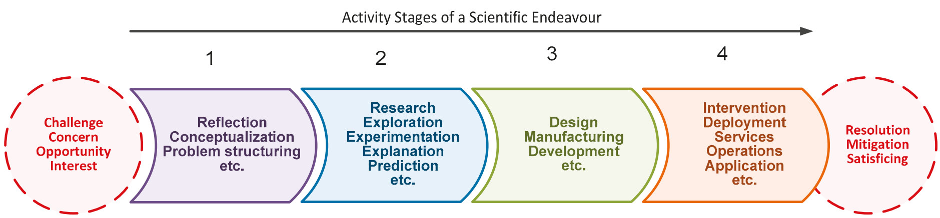

Figure 4. The basic activity stages of a scientific endeavour.

In order to simplify the discussion I will subsume the various terms used in each stage under ones I will take to stand for the "essence" of each stage, proposing that the essence of stage 1 is "reflection", stage 2 is "research", stage 3 is "design", and stage 4 is "intervention". Each of these stages of activity leads to outputs specific to that type of activity as shown in Figure 5.

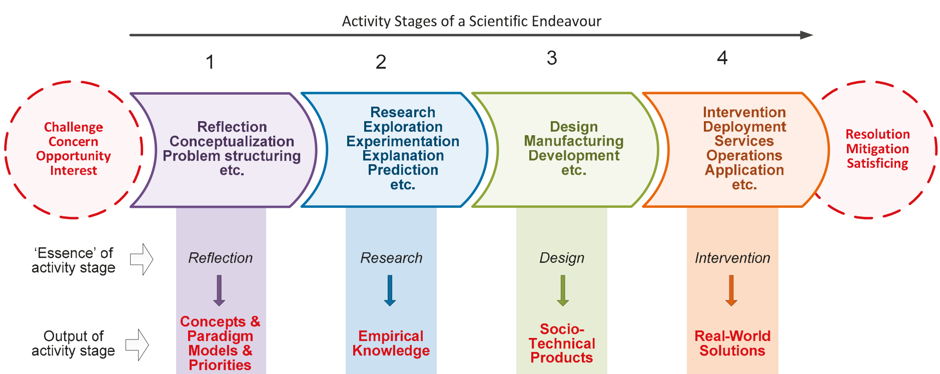

Figure 5. The typical outputs of stages of a scientific endeavour.

The type of activity in each stage is supported by methods and principles that are similar whatever the discipline under which the project is being done. The cross-disciplinary similarity of the principles, methods and outputs of each type of stage has resulted in disciplinary specializations that each have of one of the "essences" as their central concern, and we can group such disciplines together under the "disciplinary fields" of philosophy, science, engineering, and practice. These fields each lead the way in developing the principles and methods of their essential focus, but it should be remembered that every scientific discipline engages all the stages of activity. For example, the discipline of medicine has a practice element (e.g., via doctors working in hospitals), an engineering element (e.g., doctors working on medical device development in industry), a science element (e.g., doctors researching disease aetiology in laboratories), and a philosophy element (e.g., doctors developing or enforcing standards in medical ethics), so a disciplinarian can specialise in any of the field dimensions. However, in general every disciplinarian engages with all of the dimensions on every project, as illustrated in Figure 2, so, e.g., an engineering project will typically involve reflection, research, product development and product deployment. These "field dimensions" represent different kinds of hats the same person can wear on the same project without leaving their discipline. That said, the activity level of each discipline is different in the different field dimensions, tapering off away from the essential focus, as illustrated in Figure 6.

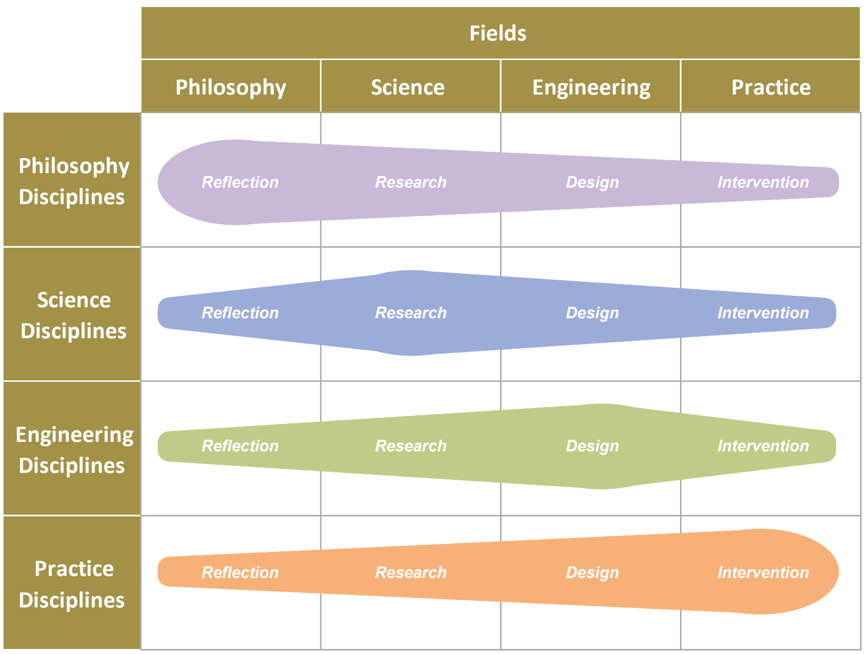

Figure 6. A scientific discipline's typical activity level per field dimension.

If we keep in mind the important observation that all disciplines cut across all the field dimensions, we can shift our analysis to looking at the fields, and so analyse the nature and evolution of the principles underlying each field of activity. This shift is helpful because we can learn from the aggregate progress in a field dimension, and the fields have overall roles from which we can learn lessons valuable for the evolution of the specialized disciplines, as will be shown below.

Figure 7 identifies the empirical disciplinary fields, and shows that they have similar structures for producing their typical outputs (in each case, methods that support activity that produce an output), but for each field the output is something different, analogous to the outputs shown in Figure 5.

In addition, we can generalize over the outputs to associate the fields with distinct roles, as also shown in the lower section of Figure 7. These roles are systemically connected, as indicated[7].

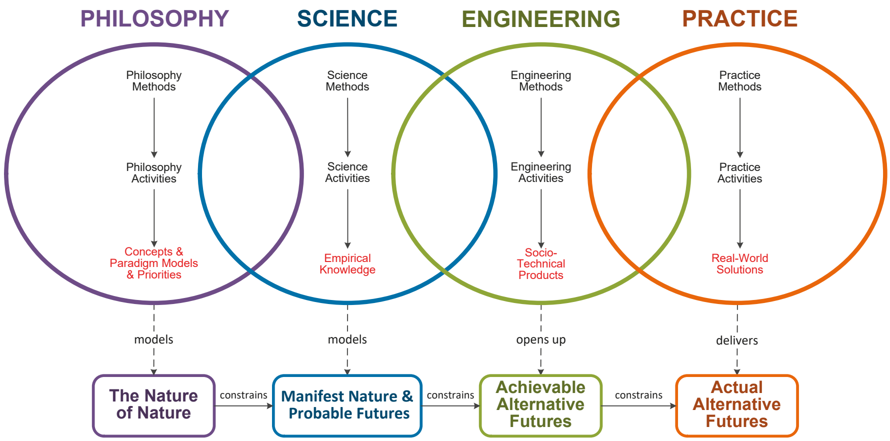

Figure 7. The basic structure and roles of disciplinary fields.

In practice, the fields are connected via common grounds, and this is indicated by the overlaps shown in Figure 7. On inspection it becomes clear that this connection happens via shared principles, as follows. The methods that underpin each field's activities operationalize principles, which (by definition) are guidelines for making judgements and taking action. Given how the phases of a scientific endeavour follow on each other, it is clear that each phase rests on the achievements of the preceding one. The natural way for this to work is for the detailed findings of one phase to be distilled into principles that can be used to develop methods for the next phase. For example, from the explanatory theories of the sciences we can distil "explanatory principles" that can not only be used to help explain further empirical phenomena, but also be interpreted as "design principles" that engineers can use for creating systems that will exhibit similar behaviours or qualities. In this way the same principles can be referred to using different vocabularies but really represent the same thing.

We can illustrate this progression in the distillation and operationalization of shared principles as shown in Figure 8. The indicated ways in which principles are referred to by differently specialised disciplinarians are indicative only, and not intended to be exhaustive.

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[7] For brevity I will gloss over the distinction between methods and methodologies, and for simplicity I will for now ignore the conceptual fields such as Mathematics and Logic. Moreover I will take the sciences to embrace the social and human sciences in addition to the so-called "hard" sciences. For pragmatic reasons I will treat Practice as if it is an integrated field, but of course in reality it is usually presented in academia as disciplinary extensions of specialized disciplines. Nevertheless the practices do fall under common regulatory frameworks, and have similar roles. Likewise for brevity I will here use the term "Philosophy" to refer only to branches of philosophy that adopt the scientific attitude as discussed earlier.

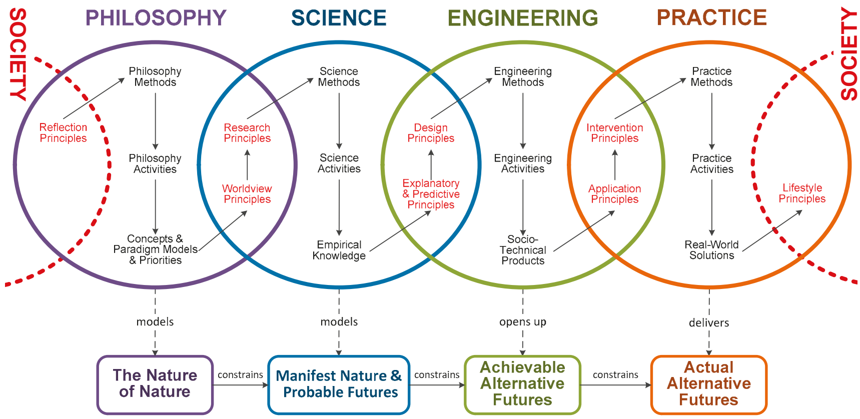

Figure 8. The scientific development of principles across disciplinary fields.

Of course philosophy methods also depend on principles, and the existence of real-world solutions can be translated into principles too, as also shown in Figure 8. These principles connect the disciplinary endeavours with society, in which reflective agents uncover the concerns that motivate the whole spectrum of scientific endeavours, and in which the delivered solutions resolve, ameliorate, or satisfice the concerns. This connection is suggested via the dashed circle segment at each end of the sequence, echoing the symbolism used in Figure 4.

Apart from the flow indicated by the solid arrows, it is important to realize that each field inherits not only the principles resulting from the previous one but also the principles and methods that produced that field's output, so we get a cumulative build-up of principles and methods from left to right. This development represents an 'inheritance' pathway, where everything becomes increasingly scientific.

Of course there is also a developmental pathway that flows from right to left. This is the "diffusion" pathway, where everything is driven by prior heuristics. In this case, heuristic methods are derived by analysing and standardising pre-established practices derived from trial-and-error activities. Heuristic principles are distilled from those methods, and the heuristics, in turn, can inspire extensions to the methods in the previous field. In this way "folk wisdom" and practical experience can spread from one field to another in the right-to-left direction.

It is important to recognize that this heuristic pathway is the historically dominant route, where people try things out first, and only afterwards try to work out better ways to do things in order to improve consistency or effectiveness or prevent common failures or negative unintended consequences. Of course in practice the "scientific" and "heuristic" pathways operate interactively, creating feedback loops as shown in Figure 9. For example, a heuristic design principle used in engineering could inspire scientific investigations leading to new explanatory theories, yielding new explanatory principles that can "upgrade" the previously heuristic design principle to a more scientific one (e.g., make it more exact, or explain what limits its viable application range).

To illustrate how the causal flows in the diagram follow a loop via the connection with society we can redraw the diagram as shown in Figure 10, with "Society" included as a field of human endeavour that connects and motivates the fields of scientific endeavour. The subjects matters of the disciplines only arise because of our capacities as sentient members of a society, and disciplinary activities only have value insofar as they contribute to addressing issues relevant to members of our society.

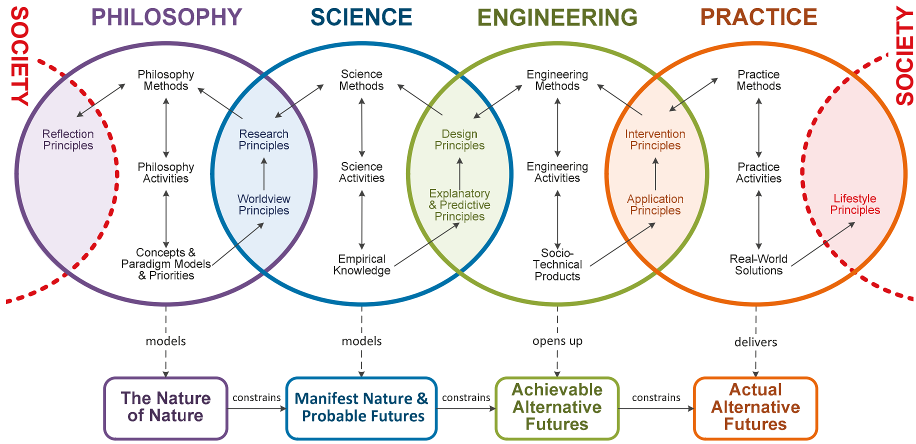

Figure 9. The interplay of scientific and heuristic principles across the field dimensions.

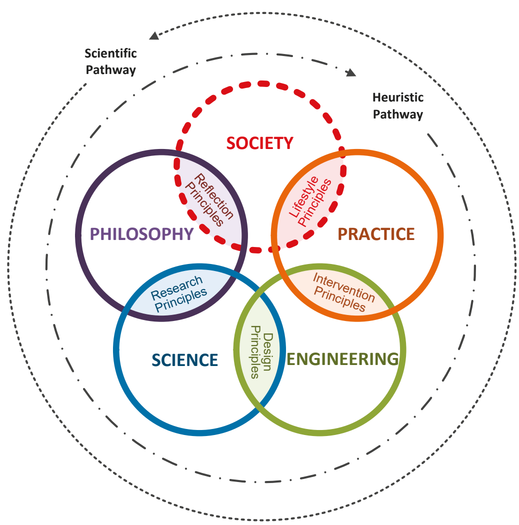

Figure 10. Interplay of pathways driving the emergence and evolution of principles across fields.

The "uncoiled" version of the diagram is easier to work with, so that is how I will continue to present it, but it should be kept in mind that the ends should be taken as connected.

The diagram in Figure 11 provides a general architecture for the relationships between the disciplinary fields, and this in turn provides a basic structure for developing a typology of the principles that they depend on or produce. I will return to this further below. For now I want to show how this general architecture of a disciplinary field can be used to frame an architecture for systemology and its high-level typology.

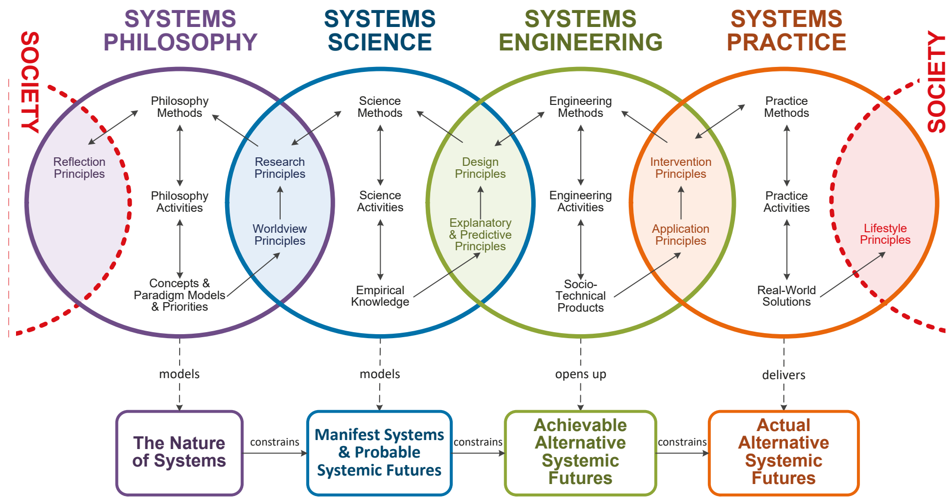

Figure 11. The architecture of systemology.

7. Connection to the Systems Perspective

Each of the mentioned disciplinary fields has a systems specialization, in which disciplinarians engage with the systemic aspects of their subject matter. This is demarcated in Figure 11 as systems philosophy, systems science, systems engineering and systems practice.

I did not add "system" adjectives inside the field-circles, in order to keep the diagram visually simpler, but such adjectives should be taken as entailed by the title over each circle, so 'inside' each we have, e.g., systems research principles, systems engineering activities, systemic real-world solutions, and so on.

Taken together, the set of these systems fields form the transdiscipline called "systemology". The systems fields are connected via the systems principles, the types of which can be separated by reference to the areas of overlap as shown. These have been color-coded in Figures 9–11 to provide a visual cue for the typology structure to be presented next.

8. Types and Sub-Types of Principles

The types of principles indicated by the overlaps shown in Figure 11 can be subdivided according to the nature of the concerns that each field dimension would attempt to address. This can be expressed in terms of a systematic breakdown of their areas of interest. For example, scientific research progressively investigates questions about:

i what things are like (how they look/behave, what they do);
ii how things work;
iii why they work as they do;
iv how they develop (come about as instances); and
v how they arise in evolutionary history (come about as kinds).

The research findings produced can be distilled into "explanatory principles" respectively characterisable as:

i classification principles;
ii design principles;
iii optimality principles;

iv developmental principles; and
v emergence/evolutionary principles.

Engineers can use these principles to develop methods for engineering design, and they would respectively interpret them as:

i design conceptualization principles;
ii functional design principles;
iii design optimization principles;
iv manufacturing/production principles; and
v innovation principles.

All of the main types of principles can be analysed in this way to identify subtypes. The diagram in Figure 12 provides a schema that does this in a provisional way for each of the scientific endeavour stages, indicating the kinds of questions addressed in each stage and the kinds of principles that are used in or result from pursuing them. Examples of systems principles are suggested in each case. This example has not been refined or optimised, but is only given to demonstrate the potential of this approach. In order to correlate the structure of the typology with the architecture given above the main types of the principles have been coloured correspondingly.

The table reflects that there are four main types of principles, respectively giving guidance for reflection, research, design, and intervention. Each type can be further subdivided into subtypes, as illustrated, as reflecting principles for guidance regarding key questions to be asked in each kind of activity. The sequence of these questions reflects what is effective for that kind of activity, and so may be peculiar to each case. For example, the sequence of the research questions listed above is defended in [57].

For brevity and simplicity no *general* structure is given in Figure 12 for subdividing the principles, the focus being rather on a natural sequence of questions for each type of activity. However, a general structure can be suggested, although developing it in detail is beyond the scope of the present paper. A short discussion of this can be given here, but for more detail please consult [58,59].

Stage	Key Questions	Subtypes of Principles	Examples of Systems Principles
Reflection	What is the issue?	Focus Principles	estabish clear boundaries
	What is the context?	Perspective Principles	systems are conditioned by systemic relationships
	What might happen?	Exploration Principles	systems change in a network balancing way
	Why does this matter?	Evaluation Principles	systemic changes have causes and consequences
	What are the risks/uncertainties?	Confidence Principles	we can only influence the systems we recognize
	What can/should we do?	Actioning Principles	dance with the systems; respect the stakeholders
Research	What is it? What is it like?	Classification Ps	systems, boundaries, relationships
	Where does it occur?	Ecological Ps	almost everything is part of a greater system
	How does it work?	Functionality Ps	emergent properties entail submergence
	Why does it work this way?	Optimization Ps	explore emergence/submergence interplay
	How did it get like this?	Developmental Ps	systems emerge from stable relationships
	How did it arise?	Evolutionary Ps	balance technical and social needs
Design	What should it be like?	Conceptualization Ps	hierarchical organization provides robustness
	How could it work?	Functional Design Ps	stability via setpoint and negative feedback
	Why should it work this way?	Design Optimization Ps	minimise resource use, maximize effectiveness
	How can we provide it?	Manufacturing Ps	integrate simpler systems to make complex ones
	Is there a better way to do this?	Innovation Ps	open systems create integration opportunities
	How can we sustain it?	Maintenance Ps	maintenance and repair depend on systems too
Intervention	Can we preserve it?	Prevention Ps	protect the hyper-nodes
	Can we change it back/recover it?	Restoration Ps	restore its structure and relationships
	Can we make it grow/multiply?	Expansion Ps	protect the systems it depends on
	Can we change it?	Transformation Ps	adjust the internal and/or external relationships
	Can we get hold of it?	Establishment PS	leverage relationship: supply - demand systems
	Can we get rid of it?	Dismantling Ps	cut at the joints in the hierarchical structure

note: for simplicity I here show input principles for reflection, output principles for research, input principles for design and input principles for intervention

Figure 12. A typology for systems principles.

Briefly, a general substructure is suggested by reflection on the variety of questions that could be posed in each field or activity stage. This variety corresponds to the kinds of knowledge one could wish to have about that (or indeed any) issue. The general case of this is represented by the general structure of a worldview, which is discussed in [6,60]. If we employ this structure we can view any particular problem as a special case of the general problem of knowing what there is, learning about it, identifying relevant values, and motivating various actions. In this way the structure of a worldview can provide us with a "checklist" if the kinds of questions we could ask in relation to any problem at every project stage. A brief example of the structure of a worldview and the questions in play relative to each worldview component is given in Table 1. Additionally, as shown in Table 1, is a matching set of research questions suggested by the worldview questions. The same can be done for the other fields/stages, as discussed elsewhere [58,59].

Table 1. The components of a worldview mapped to research questions.

Worldview Components	Worldview Questions	Research Questions
Ontology	What exists?	What is it? What is it like?
Metaphysics	What is its nature?	What does it do? How does it work? What sustains/degrades it?
Epistemology	What/How can we know?	What can we (not) know about it?
Cosmology	What is its origin/history/current state/destiny?	How did it get here? How did it get like this? What might happen to it?
Axiology	What is important and why?	Why does it work this way?
Praxeology	How should we live and why?	How should we (not) study it?

The worldview perspective gives an additional dimension for classifying principles, one that is applicable across all fields and project stages. In this way the principles in any field can be classified in terms of being ontological, metaphysical, epistemological, cosmological, axiological, or praxeological. This is, of course, an independent consideration from the distinctions identified previously. Overall this suggests that to classify systems principles at least four typological dimensions need to be considered, namely whether the principles are:

i Reflection, research, design, or intervention principles. This is the major division, but afterwards they can be subdivided as needed into:
ii General or specialized principles;
iii Heuristic or scientific principles; and
iv Ontological, metaphysical, epistemological, cosmological, axiological, or praxeological principles.

With these distinctions in hand it is now possible to establish a systematic catalogue and status assessment of systems principles and, hence, to prioritise research towards making them more comprehensive and more scientific.

9. Conclusions

One way of addressing the challenge of complexity in systems engineering is to develop more scientific principles for basing its methods on. In this paper, it is argued that improvement in systems engineering's methods depends on making the principles of systemology, of which systems engineering is a part, more diverse and more scientific. An architecture for systemology is introduced, and this shows how the principles of systemology arise from interdependent processes spanning multiple fields. On this basis a typology is introduced, which can be used to classify systems principles (and consequently the methods that operationalize them). This framework, consisting of an architecture and a typology, can be used to survey and classify the principles and methods currently in use, map vocabularies referring to them, identify key gaps, and expose opportunities for further development.

It may, thus, serve as a tool for coordinating collaborative work towards advancing the scope and depth of systemology.

Acknowledgments: I would like to thank Julie Billingham, James Martin, Javier Calvo-Amodio, Swaminathan Natarajan, and Jennifer Wilby for support and advice in developing the arguments presented in this paper. I also thank three anonymous reviewers for their helpful comments. Financial and material support for the project was provided by the Centre for Systems Philosophy, INCOSE and the University of Hull's Centre for Systems Studies.

Conflicts of Interest: The author declares no conflict of interest.

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systems

Case Report

Systems Thinking Education—Seeing the Forest through the Trees

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Received: 3 May 2018; Accepted: 6 July 2018; Published: 12 July 2018

Abstract: Systems thinking is an indispensable tool in comprehending and analyzing real-world phenomena. Observed processes are naturally composed of many interconnected components which ought to be studied jointly rather than individually. Engineering systems thinking is a very valuable skill, which helps to successfully execute multi-disciplinary projects. In high-tech companies that deal with complex and dynamic systems projects, the need for engineers with high systems thinking skills is growing. Engineers with high systems thinking skills are able to understand the big picture and the project in its entirety, both functionally and conceptually, without necessarily knowing all of the small details. Systems thinking enables understanding the entire system beyond its components, and clarifies the importance of the isolated component as part of the system as a whole. Systems thinking helps understand how sub-systems connect to one whole system, and provides solutions for the client's specifications and requirements. In addition, systems thinking enables perceiving the inter-relationships and mutual influence among the system's components and other systems. The current study examined the development of systems thinking among engineers and engineering students. In addition, the personality traits of engineers with high systems thinking skills were examined by the Myers-Briggs Type Indicator (MBTI) personality type test. This article also presents the initial results of the development of a new systems thinking study course, taught as a pilot course to industrial and management engineering students. It seems that engineers with certain personality traits can acquire or improve their systems thinking capabilities through a gradual, long-term learning process and by acquiring the necessary tools. Additionally, the study includes recommendations for the continuation of ongoing research on developing systems thinking.

Keywords: system thinking; systems approach; capacity for systems thinking; Myers Briggs Type Indicator (MBTI) personality type test

1. Introduction

Breaking down complex problems into constituent elements is often the accepted method of handling of complex assignments and questions. However, engaging in such deconstruction also often blurs perception of the problem's larger context. As stated by Senge [1]: "Systems thinking is a discipline for seeing wholes, a framework for seeing interrelationships and repeated patterns of events rather than just isolated incidences, seeing patterns of change rather than static "snapshots". It provides a scaffolding of principles, specifically tools and techniques developed in recent years, and is a discipline that seeks to discover the constructs underlying the complex, thus enabling a perception capable of discerning potential significant improvements possible with a minimum of effort (the principle of leverage). It offers us a language that expands, changes, and reshapes our ordinary ways of thinking regarding complex issues.

Clearly systems thinking will prove vital to students and graduates of technology management in their professional careers, helping them see and grasp multidisciplinary systems without necessarily being required to master the intricacies of each of their numerous parts.

2. Literature Review

The interrelationships of various system elements are the primary focus of the systems approach, as the discipline is founded on the understanding that such interactions are equally significant as the particular properties of the system components.

One of systems thinking's pioneers is Ludwig von Bertalanffy [2], a biologist who perceived systems thinking as a method of scientific investigation.

Bertalanffy [2] claimed that in order to understand what separates living matter from non-living matter, one needs to look not only at the microscopic particles, but also how they influence one another within the whole. Thereafter, he confirmed this viewpoint as a fundamental scientific approach, claiming that the only way to fully understand why a phenomenon arises and persists is to understand its parts in relation to the whole [3].

Bertalanffy [3] explained what systems thinking is: an approach that advocates viewing the issue at hand as a whole, emphasizing the interrelationships among its components rather than the components themselves, contrary to the traditional approach that understood a subject by analyzing its individual parts.

Bertalanffy [3] focused on formulating a general systems theory that could explain all systems in various fields of science since all systems are similar. The General Systems Theory (GST) contains a system of arguments, based on inter-disciplinary comparison. According to the GST, application of the theory to one specific scientific field helps solve problems and explain phenomena and processes in other fields [4].

Sterman [5,6] defined systems thinking as the ability to see the world as a complex system, in which we understand that 'you cannot just do one thing', that 'everything is connected to everything else'.

Senge [1] explained how to use the systems-thinking method in order to convert companies into learning organizations.

Senge [1] describes systems thinking as:

- A discipline for seeing wholes
- A framework for seeing interrelationships, for seeing patterns of change rather than static "snapshots"
- A set of general principles—distilled over the course of the twentieth century, spanning fields as diverse as the physical and social sciences, engineering and management
- A specific set of tools and techniques

Senge and his colleagues [7] claimed that a good systems thinker, particularly in an organizational setting, is someone who can see four levels operating simultaneously: events, patterns of behavior, systems, and mental models. It is systems thinking that brings the disciplines of personal mastery, mental models, shared vision and team learning all together.

According to Richmond [8], "Systems thinking is the art and science of making reliable inferences about behavior by developing an increasingly deep understanding of underlying structure".

Richmond [9] uses the paraphrase "forest thinking" to clarify the concept of systems thinking. According to Richmond [9], "forest thinking" involves a "view from 10,000 m rather than focusing on local trees" and "considering how the system influences systems on the other side of the line and how these latter systems influence the former system".

Richmond [10] presents four key questions about the term "systems thinking": What is it? Why is it needed? What works against its being adopted on a broader scale? And finally: What can we do to increase both the speed and breadth of its adoption?

In Richmond's [10,11] opinion, systems thinking is a continuum of activities that range from the conceptual to the technical. The adoption of systems thinking occurs when we are standing back far enough—in both space and time—to be able to see the underlying web of ongoing, reciprocal relationships, interacting cycling to produce the patterns of behavior that a system is exhibiting. You are employing a systems perspective when you can see the forest (of relationships), for the trees. You are not employing a systems perspective when you get "trapped in an event".

The term "thinking" combines learning and knowledge and includes various concepts such as: parallel thinking, holistic thinking, reductionist thinking, critical thinking, creative thinking, etc. The constructivism theory suggests that the human being is an active learner who constructs his/her knowledge of experience on his/her efforts to give meaning to that experience. In the study presented here, students were required to construct their knowledge by means of active experience and learning.

Social constructivism suggests that learners learn concepts or construct meaning about ideas through their interaction with others and with their world, and through interpretations of that world by actively constructing meaning [12].

One of the better-known researchers that refers to social constructivism theory is Vygotsky [12], who states that 'learners construct knowledge or understanding as a result of thinking and doing in social contexts'.

By implementing systems thinking, learners relate new knowledge to their previous knowledge and experience.

Systems thinking literature includes a vast range of areas of investigation, dealing mainly with the analysis of complex organizations [1,13–17], social systems, economics, curriculum design [18], social work, psychology, addiction therapy, the human body as a system, health, business, banking, personal interrelationships, the global state of affairs, environment [19], instruction methodologies for groups and teams [20,21], scientific and technological education [22], decision making [23], and project management [24].

Traditional linear thinking approaches work against an understanding of how the different parts of an organization or business work together and underplay or ignore the multifaceted nature of complex problems. It has become essential to change the nature of the curriculum to emphasize the interconnectedness of the various aspects of businesses and organizational systems as a whole [25].

It is clear that systems education, from informal learning to formal educational programs, is at the foundation of the key leverages to develop new ways of more holistic thinking to ensure systemic decision and policy making. The combination of capacity building with activities in which appropriate systems tools are being used by the end-users who will directly benefit is a critical success factor for long-term change in the way that management decisions and policy making can become systemic, rather than focusing on treating the symptoms [25,26]. Formal education in systems thinking has become essential. Many efforts are being put into ways to "infiltrate" the traditional teaching of disciplines as isolated units and to apply the systems approach in schools, universities and informal teaching programs (e.g., [25–30]). These programs can contribute significantly to the efforts of the systems community in making systems thinking and systems education become integrated into society.

Research literature presents evidence of efforts to develop systems thinking through task-oriented software, group dynamics, education, and training [31,32], demonstrating that systems thinking may be acquired or learned in a variety of ways.

Badurdeen et al. [33] presented developing and teaching a multidisciplinary course in systems thinking for sustainability. One of the reasons for using systems thinking to approach sustainability is because systems thinking is an appropriate education approach to complex problems and could be provided a kind of common language for students from different disciplines.

Another example is integrating systems thinking into sustainable manufacturing assessment.

Zhang et al. [34] presented a system of system methodologies grid in a sustainability engineering setting, where different sustainable manufacturing problems have been associated with system methodologies.

Zhang et al. [35] presented a novel approach using systems thinking principles to enhance sustainable manufacturing research and manufacturing system sustainability management. According to Zhang [35], this approach will not only benefit engineering management research by adopting systems thinking philosophies in emerging sustainable manufacturing research and practice, but will also assist enterprises in making strategic, tactical, and operational decisions by providing a deep understanding of the behavior change over time. It was also found that success in this process is of great importance to teachers/instructors/managers.

Students and graduates that demonstrate high levels of systems thinking are able to analyze customer needs and demonstrate an aptitude for coping with multidisciplinary problems in the business world.

For example, Kordova and Frank [27] conducted a capstone project with engineering students to examine whether such a multifaceted assignment discernibly improved systems thinking among participants. In this learning environment, the students constructed their own knowledge through active learning and interaction with their teammates and teaching staff. As such, the project-based learning environment supports the constructivist approach to teaching [27,36].

Some researchers refer to systems thinking as an innate ability. For instance, Hitchins [37] states that the human brain can see similarities of patterns between disparate sets of information, which presumably emanate from its drive to reduce perceived entropy, while Frank [38], Davidz and Nightingale [31] concluded that this ability is most likely a combination of innate talent and acquired experience.

Research Objectives

The research was conducted in two stages; the first stage examined factors that may potentially provide the greatest benefit in systems thinking for students and graduates of technology management. The main questions were as follows:

1. To what extent is it possible to train students and graduates for a systems-oriented position?
2. To what extent is the tendency towards systems thinking linked to personality traits?
3. To what extent is there a correlation between systems thinking capacity and supervisor evaluation?

The second stage of the study examined the extent to which it is possible to develop systems thinking capability within the framework of a designated course. Study questions were as follows:

1. To what extent is it possible to develop systems thinking capability through a designated course teaching the foundations and basic tools of systems thinking?
2. To what extent do differences exist in the ability to learn and develop systems thinking capabilities between people from different disciplines?

3. Methodology

3.1. Study Population

Stage 1:

The study population included two groups:

- The first group included 55 master's degree students from a management and technology faculty.
- The second group included 38 graduates involved in development projects in three companies that develop integrated systems for defense and homeland security applications.

Stage 2:

The study population included 21 industrial engineering and management students, 15 mechanical engineering students, and 12 psychology students.

3.2. Study Tools

Stage 1:

The first study tool was the CEST (capacity for engineering systems thinking) assessment questionnaire [39]. The capacity for engineering systems thinking characterizes the individual and can be evaluated and predicted.

The questionnaire was distributed to the first group in stage 1, before and after completing various graduate courses in systems engineering. It included 40 statement pairs, with items focusing on preferences, specifically likes and dislikes towards activities, jobs, professions, or other personality types. Respondents were asked to choose between the two statements according to their preference in each statement pair (*A* marking preference for the first statement and *B* for the second).

Here are two example items from the questionnaire:

- Item No. 17

    A. I think that every employee should gain interdisciplinary knowledge and general knowledge in several fields.
    B. I think that every employee should become an expert in his/her field. Learning more fields may lead to sciolism (to know a little about many subjects).

- Item No. 22

    A. I like to discuss the needs with the customer.
    B. B. I prefer to leave the contact with the customer to marketing experts.

The participants of the second group of stage 1 were asked to complete the CEST assessment questionnaire [39] and also the MBTI (Myers-Briggs Type Indicator) personality type test [40]. Additionally, supervisor evaluations were conducted to assess respondents' systems thinking capabilities [41].

The MBTI test is a tool to evaluate personality types using a psychometric questionnaire. The goal of the test is to help people identify their dominant preferences, tendencies, and personality traits. The questionnaire is based on the premise that people have four psychological functions through which they experience the world: Natural energy orientation, Way of perceiving or understanding and taking in information, Way of forming judgments and making choices and decisions, Action orientation towards the outside world (Lifestyle).

The result of this questionnaire is one of the 16 character archetypes, as shown in Figure 1.

The current study examined the connection between self-reported dominant personality traits (according to the MBTI research tool) and respondents' systems thinking capacity.

We examined a different kind of reliability and validity of the CEST (capacity for engineering systems thinking) assessment questionnaire. Two types of reliability were calculated: inter-judges reliability and alpha coefficient reliability. Four types of validity are presented: content validity, concurrent validity, contrasted group validity, and constructed validity.

Stage 2:

As a continuation of stage 1 of the study, we examined the extent to which it is possible to develop systems thinking capability through engaging in a designated course aimed at teaching systems thinking foundations and basic tools.

The course was based on Senge's book *The Learning Organization* [1], and on Richmond's approach [8,9] to thinking skills. The course included basic foundations of systems thinking and the five disciplines of a learning organization (personal skills and personal vision, mental models, creating a shared vision, group learning, and systems thinking).

The course stresses the ways in which changes in thinking are created and the use of the systems prototypes.

The Function		
Natural energy orientation	**Extraverted (E)** Usually open to and motivated by outside world of people and things	**Introverted (I)** Motivated internally, Prefer one-to-one communication and relationships
Way of perceiving or understanding and taking in information	**Sensing (S)** Like clear and concrete information; dislike guessing when facts are "fuzzy"	**Intuitive (N)** Comfortable with ambiguous, fuzzy data and with guessing its meaning
Way of forming judgments and making choices and decisions	**Thinking (T)** Instinctively search for facts and logic in a decision situation	**Feeling (F)** Instinctively employ personal feelings and impact on people in decision situations
Action orientation towards the outside world (Lifestyle)	**Judging (J)** Plan many of the details in advance before moving into action	**Perceiving (P)** Comfortable moving into action without a plan

Figure 1. MBTI character archetypes.

The 14-week course was conducted with two separate classes, comprised of students studying industrial engineering and management and who were also employed in the industry during their studies.

During the course, the students were exposed to the theoretical approach at the base of systems thinking and, in addition, practiced analyzing events and processes using the classic Senge prototypes [1]. Moreover, the students presented examples from their personal experience at work and from their daily reality. These examples were also examined using the systems tools.

The research hypothesis was that by integrating systems thinking tools in analyzing systems processes, the students will acquire systems thinking skills, and improve their system thinking abilities when faced with a complex problem in their organization.

Table 1 shows some examples of how to use the prototypes to analyze events.

Table 1. Examples of using the classic Senge prototypes.

Event	Tools for Analysis
An enterprise is interested in dealing with a high percentage of defective products in the production line by enlarging the required production quantities instead of establishing a process that minimizes defective products. As a result, a situation in which surplus inventory which cannot always be sold occurs.	"Moving the problem" archetype—instead of solving it examines the shifting of a specific problem to other solutions because the problem is unclear or because dealing with it comes at a high price. This is what happens when only symptoms of the problem are addressed and not the root cause. The problem can than re-occur, in the same form but also in another department.
Conflict between consumption and savings	"Success to the Successful" archetype—in which resources are allocated to the most successful activity, which makes the unsuccessful ones even more unsuccessful because they receive fewer resources. This is not necessarily the best policy for the long term.

The same CEST questionnaire distributed during stage 1 was also distributed twice in the second stage of the study—before embarking on the course and after completing it.

4. Results and Discussion

Stage 1:

Table 2 presents the comparative average scores of graduate management and technology students before and after the systems engineering course. The course lasted two semesters, and respondents completed the Frank questionnaire at three stages: at the beginning of the course, the end of the first half, and the end of the second half.

Table 2. Paired samples test.

		Paired Differences							
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference		*t*	*df*	Sig. (2-Tailed)
					Lower	Upper			
Pair 1	total_pre–total_post1	−2.63889	6.50069	1.53223	−5.87161	0.59383	−1.722	17	0.103
Pair 2	total_post1–total_post2	18.12500	32.75583	7.32443	2.79480	33.45520	2.475	19	0.023
Pair 3	total_pre–total_post2	18.19444	34.45805	8.12184	1.05886	35.33003	2.240	17	0.039

The results of stage 1 are first shown in IEEM 2015 [26].

Table 2 shows no significant difference between average scores of respondents at onset of the course and the end of the first semester (Sig. = 0.103). There was a significant difference between the mean score of respondents at the end of the first semester when compared to the end of the course (Sig. = 0.023). A significant difference was also found between the average score of respondents at onset and course conclusion (Sig. = 0.039).

These results were first presented at IEEM 2015 [28] and are in line with previous studies such as [27,31,32,38].

From these results, we can conclude that the second course provided more systems thinking tools than the first course.

One explanation for this is the nature of the course given in the second semester, which mainly dealt with systems content, as opposed to the course given in the first semester, which focused on specific content.

According to these studies, engineers or managers can report about themselves or others—that they notice details or immediately see the big picture.

Stage 1 of this study supports these findings. A significant correlation was found between supervisor ranking of systems thinking capabilities and average scores of filled-in Frank questionnaires (Sig. = 0.000, r = 0.855).

The respondents were asked to provide self-reports on their personal desire to engage in systems-related projects; a significant correlation was found between this evaluation and the results of the Frank questionnaire (Sig. = 0.000, r = 0.763).

In contrast to these findings, no correlation was found between capacity for engineering systems thinking and years of employment experience.

The established possibility of distinguishing engineering systems thinking capacity, even after only a few years of work experience, proves that apparently there are additional factors that strengthen systems thinking acquisition. Among these factors, there is also the notion of inherent potential—which seems to be an inseparable part of those candidates who received high systems thinking scores, even with little work experience (measured in years).

In addition to all of the findings mentioned above, respondents were divided into personality groups according to the MBTI questionnaire.

Study findings also support Meade's results [42], according to which 57.9% of respondents belong to the STJ (Sensing, Thinking, Judging) group. Character archetype distribution is presented in Figure 2. This finding emphasizes the fact that a significant percentage of respondents belong to particular personality groups with unique traits.

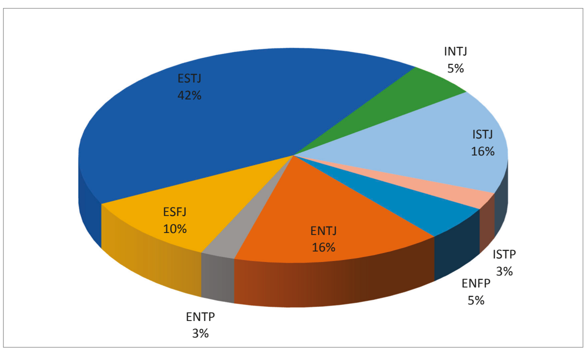

Figure 2. Character archetype distribution according to MBTI questionnaire.

Stage 2:

Analysis of questionnaire results showed no significant difference between average scores before the designated systems thinking course (Time 1) and after its completion (Time 2) (t = −0.61, Sig. = 0.5476).

Table 3 illustrates independent samples t-test outcomes.

Table 3. t-Test Outcomes.

Time	N	Mean	Std Dev	Std Err	Minimum	Maximum
1	21	54.00	8.69	1.89	39.00	66.00
2	18	55.67	8.37	1.97	36.00	72.00
Diff (1-2)		−1.67	8.54	2.74		
Time	**Mean**	**95% CL Mean**		**Std Dev**	**95% CL Std Dev**	
1	54.00	50.04	57.95	8.69	6.65	12.55
2	55.67	51.50	59.83	8.37	6.28	12.55
Diff (1-2)	−1.67	−7.23	3.89	8.54	6.96	11.05
Method	**Variance**	**DF**	**T Value**	**Pr > |t|**		
Pooled	Equal	37	−0.61	0.5476		

Figure 3 shows the normal theoretical quantiles at both time points (course onset on the left and course completion on the right). According the results of the Q-Q plots, the difference scores were not normally distributed.

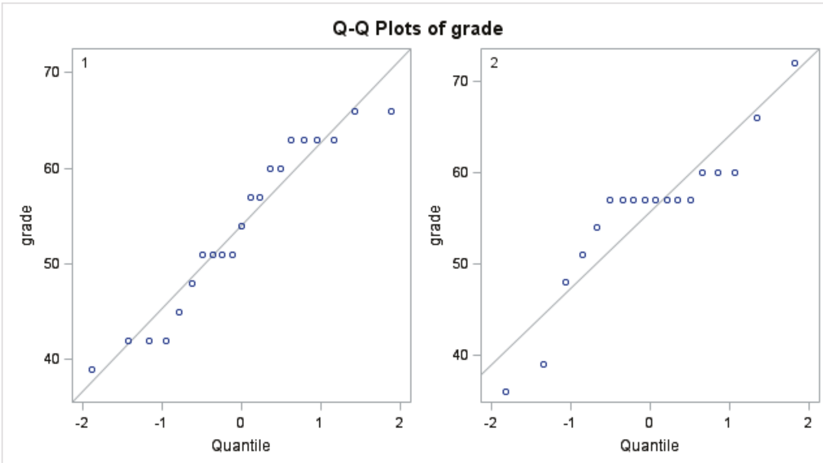

Figure 3. Q-Q Plots.

Since normal distribution was not met, we used the Wilcoxon non-parametric test to compare the scores before and after the course.

The results of Table 4 clearly illustrate no significant difference between scores at both time points (Sig. = 0.6881).

This result may be explained in several ways:

1. Small sample size. It is necessary to examine a larger group of students in order to draw stronger and more established conclusions.
2. The present course format/curriculum failed to help develop participant systems thinking capabilities; it might be necessary to revise the course curriculum and/or teaching methods.
3. The course was given to industrial engineering and management students. Perhaps these students have intrinsically high systems thinking capabilities and the course induced no improvement in their systems thinking.

Table 4. Wilcoxon two-sample test.

Wilcoxon Two-Sample Test	
Statistic (S)	374.5
Exact Test	
Two-Sided Pr >= ∣S − Mean∣	0.6881

In order to examine the last hypothesis, questionnaires were distributed to two groups whose members did not study the course: one group of students studying mechanical engineering and a second group of students studying towards their bachelor's degree in psychology.

Table 5 presents the analysis of variance when comparing total questionnaire scores among mechanical engineering, industrial engineering and management, and psychology students. This comparison was carried out during Time 1 only.

Table 5. ANOVA comparing total score among three groups (Time 1 only).

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model Error Corrected Total	2 45 47	1777.65 4971.60 6749.25	888.82 110.48	8.05	0.0010
R-Square	**Coeff Var**	**Root MSE**	**Grade Mean**		
0.263	22.30	10.51	47.12		
Source	**DF**	**Type III SS**	**Mean Square**	**F Value**	**Pr > F**
Group	2	1777.65	888.82	8.05	0.0010

Table 5 shows a significant difference exists between the three groups in total questionnaire scores at Time 1 (Sig. = 0.0010). Figure 4 indicates that the average scores of industrial engineering and management students were higher compared to those of mechanical engineering and psychology students.

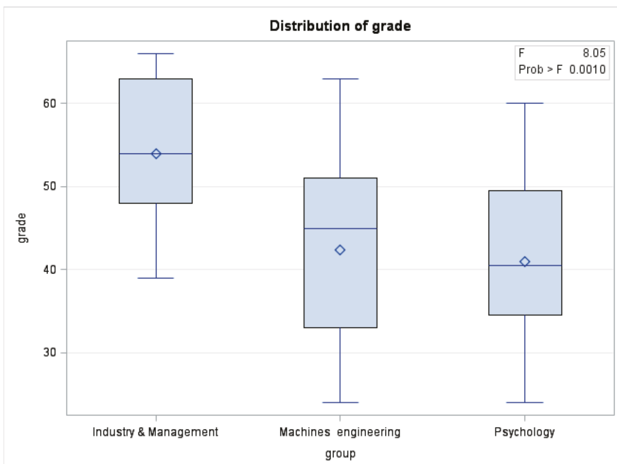

Figure 4. Grade distribution of the three groups.

Multiple comparisons were carried out to determine whether significant differences exist in total scores among the three groups, as presented in Table 6.

Table 6. Tukey studentized range (HSD) test.

Means with the Same Letter Are Not Significantly Different			
Tukey Grouping	**Mean**	**N**	**Group**
A	54.0	21	Industrial engineering
B	42.4	15	Mechanical engineering
C	41.0	12	Psychology

Since normal distribution was not met, we also used a Kruskal-Wallace non-parametric test to compare the three groups' total scores. Table 7 shows that a significant difference was found among the three groups (Sig. = 0.0028).

Table 7. Kruskal-Wallace Test (Time 1 only).

Group	N	Sum of Scores Wilcoxon Scores	Expected under H0	Std Dev under H0	Mean Score
Industrial	21	678.00	514.50	47.96	32.28
Mechanical	15	290.50	367.50	44.81	19.36
Psychology	12	207.50	294.00	41.86	17.29
Kruskal-Wallis Test					
Chi-Square	11.76				
DF	2				
Pr > Chi-Square	0.0028				

Figure 5 presents score distribution among the different groups. Industrial engineering and management students demonstrated an innate tendency for higher levels of systems thinking capability compared to mechanical engineering and psychology students.

One possible explanation for this finding may be related to the structured differences between industrial engineering and management students and those students who study other fields. It is reasonable to assume that among people who have a systems thinking approach, there is a tendency to choose a multi-disciplinary profession which, by its very definition, requires systems thinking. This means that people with an innate systems thinking approach will prefer a profession that is systems-oriented, such as industrial engineering and management, while those whose natural tendency is to see details will choose a profession that requires paying attention to the small details. Similar findings to these results were also presented is Kordova's previous study [28,36].

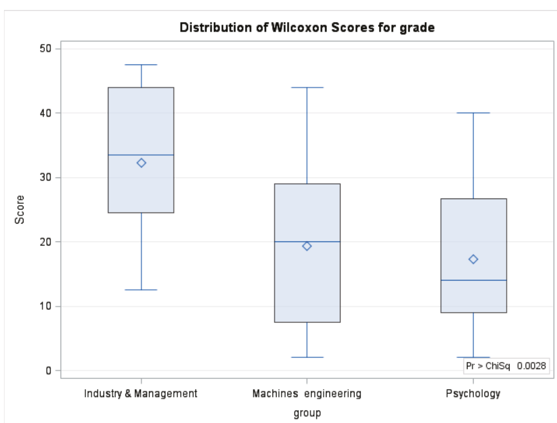

Figure 5. Grade distribution of the three groups—Time 1.

5. Summary and Conclusions

This study examined whether it is possible to train engineers and graduates for a systems-oriented position in a formal teaching environment such as systems engineering courses or systems design. The different courses teach the engineering design process, and during the course, a systems model is built; a model based on a structure related to requirements, functions, components and tests. The full model also includes systems scenarios, material and design interfaces, as well as outputs and inputs.

The main goals of these courses are: to provide knowledge about product design and development processes; to provide knowledge about different technologies in different business environments; to learn about methodologies and tools used for product and services design and development; to give students self-confidence in their personal ability to initiate and design new products/services, as well as to present and "sell" their ideas and products to clients for design and development projects.

These subjects are a main part of systems engineering studies; however, according to the results of the first part of the study, these courses focused primarily on specific engineering design processes and did not provide sufficient tools for developing systems thinking skills among the course participants. One of the study groups participated in an engineering design course, which was taught over a two-semester period as part of the master's degree program for systems engineering. The course lasted two semesters, and respondents completed the CEST questionnaire [39] at three different time points: at the beginning of the course, the end of the first semester, and the end of the second semester.

The results showed that there was no significant difference between systems thinking skills before the course and after the first semester. However, a significant difference was found between the students' average score at the end of the first semester and their average score at the end of the course. In addition, a significant difference was found between the students' average score before the course and their average score at the end of the second semester.

From these results, we can conclude that the second part of the course provides systems thinking tools to a greater extent than the first part of the course, which mainly focused on specific engineering design.

These results also show that it is necessary to create a systems thinking study course that deals with specific methodologies and systems thinking tools. These findings are in line with the results of Davidz and Nightingale [31] and Kasser [32], which showed that it is possible to acquire systems thinking through education and training.

The study also examined the systems thinking skills of systems engineers as opposed to other engineers who are partners in systems projects. It was found that the systems engineers' score on the systems thinking questionnaire was significantly higher than the other engineers' scores (Sig. = 0.000).

In addition, these engineers' managers were asked to evaluate the engineers' tendency towards systems thinking and to rank them on an ordinal scale. A significant correlation was found between this ranking and the score on the questionnaire that evaluated the engineers' system thinking ($r = 0.855$, Sig. = 0.000).

In contrast to these results, no correlation was found between the systems thinking score and number of years' experience acquired by the engineer.

These findings stress that systems engineers with high systems thinking skills are capable of understanding the general/big picture—functionally and conceptually—even without understanding all of the small details.

The study findings show that despite the difficulty to define systems thinking, people know how to evaluate the systems thinking skills of their work colleagues, and to identify those who immediately see the big picture compared to those who tend to look at the small details.

The finding that shows no correlation between systems thinking skills and number of years' experience may indicate that additional factors exist which foster this ability.

The fact that it is often possible to distinguish a capacity for engineering systems thinking, even after only a few years of work experience, proves that apparently there are additional factors that strengthen systems thinking acquisition. Among these factors, there is also the notion of innate potential—which seems to be an inseparable part of those candidates who received a high CEST score, even though they had little work experience (in years) [28].

This finding supports Frank's claim [38] that systems thinking is a combination of an acquired ability and an innate talent.

The current study found that a link exists between personality type and systems thinking skills. The study found that 57.9% of the engineers in the sample belonged to the sensing, thinking, judging (STJ) personality type, according to the MBTI questionnaire. This finding emphasizes that a large percentage of engineers have unique personalities and traits.

The second part of the study presented a preliminary attempt to develop a systems thinking study course. Since this is a pilot course, additional studies are needed with diverse sample groups in order to strengthen the claim that this type of course is likely to improve its participants' systems thinking skills.

Author Contributions: S.K.K. was the main researcher of this study who prepared the literature review, developed the study design and analyzed the results. M.F. developed the CEST (capacity for engineering systems thinking) assessment questionnaire and conducted several studies for assessing the reliability and validity of the questionnaire. A.N.M. conducted the pilot course presented at this paper. The main goal of this course was to develop systems thinking capability.

Funding: This research was supported by Gordon Center for Systems Engineering at the Technion—Israel Institute of Technology.

Acknowledgments: The authors would like to thank Guy Ribnikov for his contribution for the study findings.

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

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ISBN 978-3-03936-797-9