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Life Cycle Assessment of Protection Products for External Thermal Insulation Composite Systems

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Abstract: The energy performance and thermal comfort of buildings are decisive factors for users. Thus, solutions such as the external thermal insulation systems (ETICS) that can be installed in either new buildings or buildings under thermal retrofitting, reducing the energy consumption while improving thermal comfort, tend to become mainstream. This paper purposes to quantify the environmental and economic impacts of various ETICS protection solutions to assist in decision-making at the project phase. In this study, products available on the Portuguese market are considered. The protection products considered are hydrophobic agents, biocides, multifunctional, and self-cleaning. The products are compared by type of protection, presenting some of the most impactful components, following a multicriteria analysis of some of those products gathered into different solutions, with the objective of demonstrating the influence of the weights assigned to environmental and economic indicators. Several data-linked problems were identified, such as the quantity and quality of data available for analysis, crucial to their reliability; thus, an index for quality of information was developed in order to compare different products. In the multicriteria analysis, the weights of the sensitivity analysis between environmental and economic indicators highly influence the "best solution"; therefore, stakeholders need to clearly define their objectives.

Keywords: ETICS; life-cycle assessment (LCA); life-cycle cost (LCC); protection; sustainability

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1. Introduction

The construction sector is responsible for the consumption of approximately 40% of all stone, gravel and sand extracted; 25% of all fell wood; and 16% of all water consumed. In addition to that, it is also responsible for about 19% of global emissions of greenhouse gases (GHG) [1]. This is only at the production and construction phases; if the buildings' use, maintenance and end-of-life (EoL) phases are also considered, the sector is responsible for roughly 40% of energy consumed, 30% of raw materials extracted, 25% of solid waste production, 25% of potable water use, 12% of land use, and 33% of GHG emissions [2].

Thus, with the current goals of diminishing environmental impacts, there are numerous ways to intervene and minimize them in the various life-cycle stages of a building: from the construction phase, minimizing the use of raw materials; to the use phase, where the energy consumption can be minimized by adopting passive systems while maintaining comfort for the users; and to the improvement and expansion of the buildings' life cycle, and reuse/recycling of materials at the EoL phase.

1.1. Motivation

The choice for sustainable solutions (both environmental and economic) is central to the design of new buildings. However, most of the time, especially in construction, the choices between different solutions for an element are not direct, with equivalent solutions having different components and constructive methods.

Therefore, the motivation behind this work lies in the comparison between different solutions for the protection of external thermal insulation composite systems (ETICS) considering different products with distinct characteristics that ultimately serve the same purpose, focusing on the finishing layer of ETICS and extra protection products such as water-repellents, biocides, multifunctional, and anti-graffiti.

These products are firstly described and then studied in terms of their environmental impacts using two indicators: abiotic depletion potential (fossil fuels) (ADP (ff)); and global warming potential for a 100-year horizon (GWP100a). In addition to the environmental study, an economic assessment is also presented in the form of a present value life-cycle cost (PVLCC).

1.2. Literature Review

Sebastian Czernik et al. [3] studied the life-cycle assessment (LCA) of ETICS within a cradle-to-gate boundary for two different thicknesses and insulation materials, concluding that there is a need for more data on these materials, including more reliable and comprehensive databases.

A. Silva and J. de Brito [4] studied the service life of building envelopes through a literature review. They identified a gap in the lack of life-cycle cost (LCC) and LCA studies for these elements. This study was able to construct a database for estimating the service life for some building envelope claddings and coatings.

Annarita Paiano et al. [5] developed a study on LCA of paints. They concluded that the environmental impacts of the two paints studied might be reduced through changes to formulation (by using waste) and packaging.

Bartosz Michalowski and Jacek Michalak [6] studied the LCA of ETICS in Poland within a cradle-to-gate boundary. They were able to conclude that the environmental impacts from the production of ETICS decreased in the 2012 to 2017 interval, revealing it as a more sustainable option when selecting insulation.

The literature review supports the idea that ETICS are a strong solution for insulation in buildings and, with the evolution in the industry, the production impacts have decreased in recent years. It also supports that, despite the existence of some studies, there is still a gap in the knowledge of impacts of the different solutions for protection available, thus supporting the development of this study to aid decisions considering the service life of this element.

1.3. Scope

The scope of this work is to assess and characterize the environmental and economic impacts of commercial products to be used on ETICS to enhance their durability. Some components of those products are identified to demonstrate that, often, most environmental impacts are generated by components that are incorporated only in small quantities in products and that many of these components are recurrent in numerous products.

However, an in-depth study of the products' components is not presented, falling beyond the scope of this work, with only a brief comparation of the weight of impacts for the most impactful components. A study of the products is the main objective, finalizing with a comparation between different equivalent solutions of ETICS protection with a multicriteria sensitivity analysis considering environmental and economic indicators.

2. Materials and Methods

This work began by gathering and compiling the information available through the manufacturers, as described hitherto. The types of materials, developed methods, information gathering, and impact assessment procedure are described in this section.

2.1. LCA Methodology

The LCA methodology allows for the quantification and assessment of the environmental performance of products and/or services. It allows to for the comparison between various products manufactured in different factories, in different countries, and/or in distinct conditions. This methodology is normalized by the Institute of Standardization and Normalization (ISO) in the form of the standards ISO14040:2006, ISO14044:2006, and ISO15643:2010-2017.

To assess environmental impacts, two indicators were considered (ADP (ff) and GWP100a) due to their relevance in the 2030 European Union (EU) Agenda to address climate change and the 2050 targets [7,8], representing ADP (ff)—the embodied energy from non-renewable sources, and GWP100a—the CO_2-equivalent emissions from a specific process.

2.2. Materials

With the main aim of comparing different protection solutions for ETICS, several types of products were considered: hydrophobic products, biocides, anti-graffiti and multifunctional products.

2.2.1. ETICS

The ETICS is a system that envelops the facades of a building from the outside. Its main purpose is to improve the thermal qualities of buildings, both new and under renovation/reconstruction. ETICS can help buildings maintain constant temperatures throughout the year in various weather conditions while passively reducing the consumption of energy. This solution has gained ground in the last 15 years in Portugal, having increased from 200.000 m^2 applied in buildings in 2006 to 2,400,000 m^2 in 2010 [9,10].

Thus, the study of the life cycle of this solution, considering the various protection products that exist on the market, is of significance. This work considers only the last layer, which is usually a plastic coating and sometimes a current paint [11–13].

2.2.2. Hydrophobic Agents

Hydrophobic products are one of the oldest forms of buildings protection due to water being the main agent of construction degradation [14,15]. This type of protection can be divided in two, according to the medium (or base) in which the active raw material is diluted: water or solvent. The need to diminish the environmental and the health impacts that the solvent-based products have in both the environment and in animals (including humans) has accelerated the ongoing transition from solvent to water-based products.

Hydrophobic products can also be divided on how they act: film formers or penetrating products. The latter can be divided into pore-blockers and impregnating solutions [16–19]. From these, the impregnating solutions are most common in the market, and are mostly based in silicone resins such as silanes and siloxanes [17,19,20]. These products form an apparent contact angle of at least 90°, resulting in added difficulty for water to adhere to surfaces [21].

2.2.3. Biocides

Microorganisms tend to adhere and form colonies in the pores of cement-based mortars, resulting in changes in pH that affect the cement and subsequent layers of protection while producing stains on façades that reduce the aesthetic appeal of buildings resulting in the need for maintenance of these surfaces [22,23]. However, biocidal products are toxic to living organisms, which makes this category of product highly regulated by the European Union (EU), namely by ECHA (European Chemicals Agency) [24].

2.2.4. Anti-graffiti

Graffiti are, historically, words, scribblings or drawings made on surfaces in an unauthorized way, through carving or other means [25]. Nowadays, graffiti are a form of vandalism that consists of drawings made essentially with aerosol paints on any surface, in an indiscriminate way, without any sort of concern regarding the historical value of the buildings or definitive alterations of the surfaces on which the paint is applied [26–28].

The anti-graffiti products can be divided into three categories: sacrificial, semi-permanent, and permanent. This categorization takes into consideration the amount of cleaning cycles the protection endures. Sacrificial products are removed with every cleaning cycle with the graffiti, and usually consist of a type of wax with hydrophobic and oleophobic properties [26,28,29]. Permanent products resist a few cleaning cycles (usually more than 10) having a service life of about 10 years consisting mainly of epoxy resins, polyurethane, acrylic-siloxane, or fluorocarbon copolymers [30,31]. Semi-permanent products can be either a mixture of both permanent and sacrificial products, forming a two-layer system with a permanent base that is coated with a sacrificial one; or a single layer product that has a service life of more than one but less than three to five cleaning cycles [26,28,30].

2.2.5. Multifunctional

Multifunctional products are defined by their ability to protect a surface from more than one aggressive agent. Self-cleaning products are considered in this category, as their ability to self-clean is linked to the hydrophobicity of the surface [32,33].

Multifunctional products can be categorized as film-forming, superhydrophobic, and photocatalytic. Film-forming products are similar to transparent paint that can be applied on top of other finishing layers and that can have hydrophobic, biocidal, and even self-cleaning properties. Superhydrophobic products consist of formulations based in silicon resins with improved hydrophobic abilities that facilitate the forming of water beads that roll through the surface, biomimicking the lotus effect [33–35]. Photocatalytic products are based in formulations of titanium dioxide (TiO_2) that can form a hydrophilic surface when exposed to UV radiation and become slightly hydrophobic when they cease to receive UV radiation. This mechanism allows the TiO_2 to decompose pollutants, when exposed to UV radiation, by the creation of super oxides and hydroperoxide radicals while in the presence of water [35–39]. When the surface ceases to receive UV radiation, it becomes hydrophobic, and the water film that was formed with the radiation can drain and drive all the pollutants off the surface, while also hindering biological growth [37,40–42].

2.3. Data Collection and Quality Assessment

The environmental LCA is a data-intensive analysis. Therefore, this work focuses, in a first approach, on gathering as much data as possible from protection products available on the Portuguese market, followed by their organization, so different solutions can be compared in a meaningful way. The referred data were collected from technical data sheets (TDS) and safety data sheets (SDS) for all products considered, as well as from European technical assessments (ETA) for the products that belong to certified ETICS solutions. These data consist of all information about products' consumption rates, dilutions, components, quantities, densities, and all parameters with influence on either the yield or composition of each product.

In order to rate the products gathered by their level of information, an index, the information quality index (IQL) was developed as described next.

2.3.1. Information Quality Level

Due to the problems found regarding the quantity and quality of information provided by manufacturers, a standardized procedure with well-defined parameters to assess the quality of information available is needed.

This is achieved with the development of the IQL index. This index considers the amount and quality of information, both in the identification of the components and in their proportions in each product. This index attributes a value on the interval [0, 5], with 0 being equal to "no information" and 5 to "complete information", as shown in Table 1.

The components are divided into three categories:

- **Global**: unspecific components that are not active components nor the base (fillers, pigments, and others);
- **Active components**: main constituents that provide the principal characteristics to the product (such as silanes on hydrophobic products);
- **Base**: means of application, which can be solvent or water.

Table 1. Information quality level.

	Components						
IQL	**Global**		**Active Component**		**Base**		
	Id.	**%**	**Id.**	**%**	**Type**	**Id.**	**%**
0	No	0%	No	0%	No	No	0%
1	Partial	0%	No	0%	No	No	0%
2	Partial	<10%	Partial	0%	No	No	Infer
3	Partial	Infer	Partial	Infer	Yes	No	Infer
4	Partial	50%	Yes	Infer	Yes	Partial	100%
5	Yes	100%	Yes	100%	Yes	Yes	100%
Key:	Id.:	Component identification					
	Partial:	Components are partially identified					
	Infer:	Quantities are inferable					
	Type:	Type of base is determined					

In each component category, it is first defined whether the respective components are listed in any of the technical documents available, mainly TDS and SDS. Then, it is determined if their percentages in the finished product are enunciated and, if so, to what level. With this information, the IQL is determined for that product.

The "inferability" concept consists of attributing reasonable percentages to a known component of a determined product that, in its TDS or SDS, does not have a quantity defined. For example, in a water-based silane-based hydrophobic product, the silane content is, on average, 8.37% (with a minimum of 2.4% and a maximum of 12.5%). Thus, it is reasonable to assume a value of 10% in products of this type that do not clearly enunciate the quantity of silanes. This concept allows the use of reasonable values and applies them to products that would otherwise be dismissed for lack of information.

Next, as most times only some information is presented, the "partial" concept was needed to take this into account. This concept is mostly used to distinguished between IQL 4 and IQL 5, since in most cases, available information does not guarantee that the components are fully listed. This can only be inferred when 100% of the formulation is achieved for the components listed on the SDS.

Regarding the base, the "Type" column refers to the identification of the base. If the documents consulted refer to the product as solvent- or water-based in any way, then the answer in this column is "Yes."

The percentages on Table 1 refer to the quantity of information available for each type of component. For example, in global components, if a given product has global components that are responsible, in total, for 50% of its formulation, but only one global component is listed in the SDS with a proportion of 3% of the whole product, that means that only 6% ($3/50 \times 100 = 6\%$) of the global components have information, therefore, an IQL of 2 is attributed to the global components.

The IQL value attributed to each product is always the lower between the three categories considered (global, active, and base). For example, if a product discloses all the active component and base information but has an IQL of 2 in the global components, its final IQL is 2, and therefore is dismissed.

The minimum IQL considered in this study is 3. Levels in the interval [0, 2] are automatically dismissed, and levels [3, 5] are considered.

The approximations considered make assumptions that would work across all products. This is a relative measure, but with the same assumptions made on all products and their evaluation being similar, it is reasonable to assume that the results are comparable.

2.3.2. Data Normalization

The data were collected in different units, with different presentation formats that vary from producer to producer, and, even within the same producer, vary from product to product (e.g., from different units for the consumption rate to various dilutions and number of coats to apply). All characteristics were consolidated into a whole consumption rate in kilograms per square meter (kg/m^2). Therefore, data normalization is the process used to transform all the data gathered into the same units and formats.

2.3.3. Environmental Data Gathering

After the collection of all available data, mainly about the components and their proportions, the next step was the attribution of existing production processes to each component to calculate the impacts using the ADP (ff) and GWP100a indicators (indicator chosen for their significance in the European 2030 and 2050 objectives [7,43]) for each product.

The SimaPro software and the "CML-IA Baseline V3.05" [44,45] were used for the assessment of environmental impacts. The processes needed are available from the Ecoinvent v3 [46] database.

The next challenge that this work encountered was in the attribution of those processes to the products studied. The problem is that not all chemicals and components in the SDS are represented directly in the database. Thus, it was necessary to choose reasonably similar processes by searching for different nomenclatures for each component or, in the worst-case scenario, attributing processes from the same chemical family. For this research, ECHA [24] (for searching the different CAS—unique number of a given chemical, attributed by the Chemical Abstracts Service, Columbus, OH, USA) and PubChem [47] databases were used, since both have various nomenclatures for every chemical substance listed, including commercial names.

After this attribution of processes to every single component, the impacts of the processes in the ADP (ff) and GWP100a categories were collected.

2.3.4. Functional Unit

The environmental impacts collected are presented for a declared unit—kilogram (kg)—that is not meaningful in the context of this work. Thus, the definition of the functional unit is an absolute requirement.

The objective of this work is to quantify the environmental and economic impacts in the service life of protection solutions for an ETICS-covered wall. Thus, the functional unit considered is the manufacture of each material to coat a square meter (m^2) of wall. This unit allows the modelling of various protection solutions, providing the grounds for presenting results per square meter of any and all combinations of protection products.

Thus, knowing the consumption rates, the environmental impacts in the declared unit of the components, the proportions of the components in each product, and having defined the functional unit as (m^2), it was possible to first calculate the environmental impacts for the products in the declared unit, using the proportions and the impacts gathered for every component in the databases considered; and then, using the density of the products and their whole consumption rate, it was possible to transform the impacts from the declared unit to the functional unit, reaching values of (MJ/m^2) for ADP (ff) and (kg eq CO$_2$/m^2) for GWP100a.

3. Results

In this study, various products available on the Portuguese market were considered. However, when a category of products had more than one product, only the representative products were considered for the environmental analysis.

These "mean" products are averages from all the products considered in each category, and are represented by the letter "Z", followed by a two-digit number unique to each product and, lastly, two letters between brackets that identify the type of product: (HF) for hydrophobic products; (BC) for biocide; (AG) for anti-graffiti; (MF) for multifunctional; (TT) for finishing layers not considered in ETA; (AE) for finishing layers considered in ETA.

Real products, present on the market, follow the same coding logic, but are represented by a letter from "A" to "Q", one per manufacturer.

The environmental impacts of the different products' types are presented, as well as a study of the most impactful components, per weight and per environmental impact category.

3.1. Hydrophobic Protection

In total, 26 hydrophobic products were considered in this study, 3 being of the 100% active component type, 12 water-based, and 11 solvent-based.

The hydrophobic products are extensively present on the market and can be divided into two categories: water-based and solvent-based. A third category is also considered, that of the 100% active component, but will be later included in water-based products. The environmental impacts from these two main categories are quite different, with the solvent-based products presenting impacts in ADP (ff) and GWP100a much higher than the water-based ones. In Table 2, the environmental impacts of the representative products are presented.

Table 2. Environmental impacts of the representative average hydrophobic products.

Product	ADP (ff)	GWP100a
	(MJ/m^2)	(kg eq CO$_2$/m^2)
Z01(HF)	4.168	0.384
Z02(HF)	29.946	1.067
Z10(HF)	14.510	1.480
Z03(HF)	17.244	0.819

The products listed in Table 2 represent the following categories:

- Z01(HF)—average from the 12 water-based hydrophobic products;
- Z02(HF)—average from the 11 solvent-based hydrophobic products;
- Z10(HF)—average from the 3 100% active raw material products;
- Z03(HF)—average from the 26 hydrophobic products.

In the next step, based on the impact of the different components, Table 3 was built to characterize the most relevant components of the water-based hydrophobic products studied in terms of environmental impact and of their proportion in the final product.

Table 3. Average contribution of the most relevant components per water-based hydrophobic product.

Components		ADP (f.f.)	GWP100a
Description	**Average %**	**%**	**%**
Silane or	8.37%	90.2%	90.4%
Siloxane or	9.03%	86.5%	86.0%
Silicone	11.67%	97.9%	98.5%
Water	90.26%	0.1%	0.1%

As easily observed, water is the main component by kilogram per kilogram of product, but its environmental impact is irrelevant, being 0.1% on average. On the contrary, silicone-based products, which constitute the active raw material in hydrophobic emulsions, despite representing only about 10% in average of the composition of each product, are responsible for, on average, more than 85% of environmental impacts in ADP (ff) and GWP100a.

In the case of the solvent-based products, the number of relevant components is higher, not only because there are distinct types of solvents, but also because there are more active components soluble in solvents than in water. In Table 4, the average proportion and relative impacts of these components in the final products are presented.

Table 4. Average contribution of the most relevant components per solvent-based hydrophobic product.

Components		ADP (ff)	GWP100a	Components		ADP (ff)	GWP100a
Description	**Average %**	**%**	**%**	**Description**	**Average%**	**%**	**%**
Silane or	10.6%	10.1%	26.5%	**Solvent**	51.4%	61.5%	41.0%
Siloxane or	8.3%	19.6%	48.8%	**Ethanol or**	75.0%	69.4%	77.6%
Silicone	21.4%	25.0%	38.8%	**White spirit or**	76.3%	69.5%	26.9%
Acrylic Resin	43.0%	44.3%	70.0%	**Naphtha or**	86.7%	82.5%	45.2%
Hydro-oil	3.4%	5.8%	22.2%	**Kerosene**	60.0%	47.5%	12.7%

In this case, the environmental impact contribution is more balanced between the active raw materials and the solvent base.

3.2. Biocidal Products

In total, five biocidal products were considered in this work, and the representative average product Z04 (in both A and B forms) represents the average of these products.

Biocidal products are available on the market in the form of additives that are added to paints to afford them biocidal properties. Table 5 presents the environmental impacts of the representative average products for biocidal additives.

Table 5. Environmental impacts of the representative average biocidal additives.

Product	ADP (ff)	GWP100a
	(MJ/m^2)	**(kg eq CO$_2$/m^2)**
Z04(BC)_A	0.171	0.013
Z04(BC)_B	0.509	0.040

There are two Z04(BC) products because the average of the impacts was calculated in different ways. In the first one (Z04(BC)_A), the average environmental impact was calculated using the final values of the four additives considered, directly, considering an average paint consumption rate of 1.04 L/m^2 (which represents the average of the considered finishing layers). For Z04(BC)_B, the values of the environmental impacts were calculated for the same four products, but first in the declared unit and then transformed to the functional unit considering the consumption rate of the paint in which they will be incorporated. The Z04(BC)_A exemplifies a situation without a specific paint to add the biocide, while Z04(BC)_B exemplifies a situation in which it is needed to add the representative average biocide to a specific paint, so that the impacts of the biocidal additive consider the specific properties of the paint (the differentiation between Z04(BC)_A and Z04(BC)_B will be important in subsequent sections, where the average biocide is used in specific finishing layers at different consumption rates).

In Table 6, the average environmental impacts are presented in relation to their proportion in each product. In this case, as in the water-based hydrophobic products, the water, despite representing more than 80% of the product on average, has an environmental impact inferior to 0.5%. On the contrary, the biocidal agents, despite being incorporated at low percentages in the final product, represent higher environmental impacts, such as DCOIT, which on average represents about 2.5% of the proportion of the product but is responsible for more than 68% of the impacts in ADP (ff) and GWP100a.

3.3. Anti-Graffiti

In the case of the anti-graffiti products, their number on the Portuguese market is very small, and the information disclosed by the producers is quite low. Therefore, the number of products with an IQL equal or superior to 3 is only five, three of which are permanent, one being sacrificial and one semi-permanent, as presented in Table 7.

Table 6. Average component proportion in biocidal additives related to average environmental impacts.

Components		ADP (ff)	GWP100a	Components		ADP (ff)	GWP100a
Description	**Average %**	**%**	**%**	**Description**	**Average %**	**%**	**%**
IPBC	0.7%	37.0%	40.0%	**Zinc oxide**	2.9%	26.1%	26.6%
DCOIT	2.5%	75.2%	68.3%	**Propane-2-Ol**	2.5%	99.7%	99.3%
Terbutrine	1.0%	65.0%	64.4%	**Diuron ISO**	10.0%	82.3%	82.3%
Water	81.9%	0.4%	0.5%				

Table 7. Commercial and representative average anti-graffiti products.

Product	ADP (ff)	GWP100a	Type	Service Life		IQL
	(MJ/m^2)	(kg eq CO$_2$/m^2)		Years	Cleaning Cycles	
C01(AG)	0.497	0.051	Semi-permanent	NA	1	3
Q08(AG)	8.076	0.116	Sacrificial	5	1	4
Z06(AG)	19.603	2.074	Permanent	NA	NA	NA
Z07(AG)	13.476	1.278	NA	NA	NA	NA

Z06(AG) represents the average of the three permanent products and Z07(AG) represents the average of all five anti-graffiti products, regardless of type.

In these products, there is no common ground in terms of active components, as is observable in Table 8, where the main components of the anti-graffiti products are presented. These main components are those that either represent a high proportion of the formulation of the product or are responsible for a large part of its environmental impact. In this case, it is important to take into consideration the IQL, which is between 3 and 4 for all products. As this is a relative means of measuring the quality of information, and the full information of these products is not disclosed (for any of them), it is difficult to accept that these results are sufficiently reliable for all of them. The best results are those of the permanent products, both due to their IQL index and the fact that three products are accounted for; therefore, some error is eliminated in averaging them into Z06(AG). The sacrificial product Q08(AG), being a wax, has a formulation of 40% ME wax and 60% water that is reasonable and is considered in the next steps of this study. The semi-permanent product C01(AG), given its IQL of 3 and its lower-than-expected environmental impacts, will not be considered any further.

Table 8. Main components of anti-graffiti products.

Product	Components		SimaPro Process	ADP (ff)	GWP100a
	Description	**%**		**%**	**%**
F03(AG)	Silsesquioxanes	25.0%	Polydimethylsiloxane {GLO}	86.7%	93.2%
	Water	61.7%	Tap water {RER}	0.0%	0.0%
Q08(AG)	Wax ME	40.0%	Paraffin {GLO}	100.0%	99.9%
	Water	60.0%	Tap water {RER}	0.2%	0.0%
Only the SimaPro process prefix is presented, but all processes are followed by "| market for	Cut-off, S"					

In Table 8, a permanent product (F03(AG)) and a sacrificial one (Q08(AG)) are represented, with their most impactful raw materials in both percentage of weight in the finished product and in environmental impacts.

As the ingredients vary wildly between the different products, the component study has no value here; therefore, it is not presented as it was before.

3.4. Multifunctional Products

Multifunctional products are a small category, with only four products on the market, being one superhydrophobic and oleophobic, two photocatalysts and one film-forming. However, in this case, the small number of products can be attributed to their relatively recent development, especially in biomimicking the lotus effect (which requires recent nanotechnology developments to create the nanostructures needed to generate the superhydrophobicity that provides the self-cleaning ability) and developing photocatalytic products, which are also very reliant on nanotechnology. In Table 9, all studied multifunctional products are presented with the representative product for the photocatalysts (Z08(MF)).

Table 9. Commercial and representative average multifunctional products.

Product	ADP (ff)	GWP100a	IQL	Type
	(MJ/m^2)	(kg eq CO$_2$/m^2)		
D20(MF)	17.203	0.614	3	Superhydrophobic oleophobic
F04(MF)	6.464	0.432	4	Photocatalyst
F05(MF)	6.815	0.422	4	Photocatalyst
H03(MF)	8.949	0.499	4	Film
Z08(MF)	6.639	0.427	-	Photocatalyst

Z08(MF) represents the average between F04(MF) and F05(MF), both of which are photocatalytic products with a TiO_2 base. The film product represents a water-based transparent paint with no pigment added, which is self-cleaning, hydrophobic, and has some biocidal ability. The D20(MF) product is closer to a pure self-cleaning product; however, as discussed, this capability of self-cleaning has the secondary effects of hydrophobicity and of hindering the growth of microorganisms. In Table 10, the main components of every product considered in this study are presented.

Table 10. Main components of representative multifunctional products.

Product	Components		SimaPro Process (Market for ǀ Cut-off, C)	ADP (ff)	GWP100a
	Description	%		%	%
D20(MF)	Silane	20.0%	Dimethyldichlirosilane {GLO}	20.8%	59.7%
	Solvent	77.0%	Solvent, organic {GLO}	74.8%	33.1%
F04(MF)	Ethyl silicate	10.0%	Tetraethyl orthosilicate {GLO}	32.3%	27.8%
	Titanium dioxide	20.0%	Titanium dioxide {RER}	46.2%	60.7%
	water	60.0%	Tap water {RER}	0.0%	0.0%
H03(MF)	Methil methacrylate	1.9%	Methyl methacrylate {RER}	13.8%	16.3%
	Acrylic resin	9.8%	Methyl acrylate {GLO}	39.4%	32.7%
	Water	78.7%	Tap water {RER}	0.0%	0.0%

As in other products already presented, water-based products, such as photocatalytic ones, have lower environmental impacts, with the photocatalytic agent (TiO_2) being the main contributor to the environmental impacts. In the film-forming product (H03(MF)), the main part of the environmental impact results from two components that represent about 12% of the formulation but are responsible for more than 40% of both ADP (ff) and GWP100a impacts. In the superhydrophobic product (D20(MF)), being solvent-based, the environmental impacts of the silane and solvent parts are directly proportional to their proportion of the product.

3.5. ETICS Finishing Layers

In this category, the finishing layers described in the ETA of each ETICS are considered. However, only a few of the certified systems have TDS and SDS available and, among these, only a few provide relevant information in those documents. Adding to that, one specific manufacturer provides solutions with paints that are not mentioned in their certification document. However, that information was considered, but is presented in a different way: finishing layers in ETA have an "(AE)" suffix, while the paints do not present in ETA are presented with the "(TT)" suffix. In Table 11 it is possible to assess the environmental impacts evaluated for these products.

Table 11. Commercial finishing layers considered in this study, with two control products.

Product	ADP (ff) (MJ/m^2)	GWP100a (kg eq CO_2/m^2)	IQL
H04(TT)	8.265	0.625	5
H05(TT)	11.603	1.064	4
H06(TT)	7.910	0.606	5
A05(AE)	40.811	3.971	3
A06(AE)	40.811	3.971	3
A07(AE)	5.528	0.260	3
H07(AE)	27.232	2.053	5
K01(AE)	104.139	10.143	3
K02(AE)	104.139	10.143	3
K03(AE)	10.829	0.505	3
X01	32.66	1.98	EPD
X08	10.54	0.38	EPD

In this case, it was possible to verify the accuracy of the calculations and approximations needed to reach meaningful results. That verification was made by comparing the results achieved (with the calculation methods used in this work) with the results of the products X01 and X08. These products are paints not available on the Portuguese market (so they were not considered in this study) but whose manufacturer has an EPD available for consultation with the values presented above for ADP (ff) and GWP100a. Their role here is as control products, since EPD is a verified document and these values can be used as a comparation to assess if the values calculated in this work are plausible.

In Table 12, the main raw materials of four ETICS finishing layers are shown, presenting their percentage of the final product, and their contribution of environmental impacts. The product A05(AE) was considered despite 70.3% of unknown components. However, the unknown part is most probably some kind of filler such as crushed limestone with high volume and low environmental impact (as observed in the product K01(AE)).

Table 12. Main components of four ETICS finishing layers considered in this work.

Product	Components		SimaPro Process (Market for | Cut-off, C)	ADP (ff)	GWP100a
	Description	%		%	%
H04(TT)	Terbutrin	2.4%	Triazine compound, unspecified {GLO}	11.5%	10.3%
	Titanium dioxide	24.2%	Titanium dioxide {RER}	53.4%	62.1%
	Water	46.8%	Tap water {RER}	0.0%	0.0%
A05(AE)	Copolymer	10.0%	Polydimethylsiloxane {GLO}	99.2%	99.5%
	Unknown	70.3%	Unknown	0.0%	0.0%
H07(AE)	Terbutrin	2.5%	Triazine-compound, unspecified {GLO}	26.5%	23.8%
	Titanium dioxide	10.0%	Titanium dioxide {RER}	49.2%	57.5%
	Water	27.5%	Tap water {RER}	0.0%	0.0%
K01(AE)	Copolymer	20.0%	Polydimethylsiloxane {GLO}	99.6%	99.7%
	-	65.6%	Limestone, crushed, washed {CH}	0.1%	0.0%

The products with the component copolymer were considered siloxanes because polydimethylsiloxane is one of the most environmentally impactful active components, so it was a conservative choice to consider this process.

3.6. Economic and Environmental Analysis—Case-Studies

In this section, the solutions studied from an environmental point of view for singular application are studied for the average service life of an ETICS.

It was determined, based on the ETAG 004, EAD 0400-00-0404 [11,13], and on other literature [48,49], that a reasonable average value for the service life of an ETICS solution is 30 years [48]. The next challenge is the determination of the service life of each protection product and of their effect on the service life and maintenance of ETICS. As this information does not exist, a "worst case scenario approach" was considered. This means that, from now on, the service life values indicated by the manufacturers will be considered for all products and, after that interval of time, a new coating will be necessary. These values are presented in Table 13 for the products considered in the case-studies.

Table 13. Relevant data for the products considered in the case-studies.

Type	**Product**	**Cost**	**Service Life**	**ADP (ff)**	**GWP100a**
		(EUR/m^2)	**(Years)**	**(MJ/m^2)**	**(kg eq CO$_2$/m^2)**
ETICS finishing layer	A05(AE)	8.87	10	40.81	3.97
	A06(AE)	9.11	10	40.81	3.97
	ZA0(AE)	8.99	10	40.81	3.97
Biocide	A03(BC)	48.49 *	5	3.72 *	0.24 *
Water-repellent	A01(HF)	3.14	5	2.51	0.25
Multifunctional	F04(MF)	5.00	10	6.46	0.43
Anti-graffiti	F03(AG)	5.00	5	12.26	1.11

* Values for a ZA0(AE) consumption rate of 1.3 l/m^2.

The ZA0(AE) product represents the average of A05(AE) and A06(AE). In terms of economic assessment, an LCC is considered, specifically a fixed cost approach, in which the inflation rate is not considered, with a discount of values from the future to the present having in consideration a secure investment rate [50,51]—in this case, certificates of the Portuguese treasury with an average rate of 1.38% [52]. The maintenance plans are shown with planned interventions in 5-year increments until the end of life (EoL) of the ETICS. The solutions S01_2 (Min) and S01_2 (Max) are border solutions and represent best- and worst-case scenarios, respectively. The solution S01_1 is the one to compare to S02 and S03.

In Table 14, all the considered solutions are presented. In each year it is defined as the percentage of product to reapply.

Table 14. Maintenance solutions considered.

Solution		**Year**						
	Product	**0 %**	**5 %**	**10 %**	**15 %**	**20 %**	**25 %**	**30**
S01_1	ZA0(AE)	100%	0%	50%	0%	50%	0%	EoL
S01_2 (Min)	ZA0(AE)	100%	0%	25%	0%	25%	0%	EoL
S01_2 (Max)	ZA0(AE)	100%	0%	100%	0%	100%	0%	EoL
S02	ZA0(AE)	95%	0%	0%	0%	0%	0%	EoL
	A03(BC)	5%	0%	0%	0%	0%	0%	
	A01(HF)	100%	100%	100%	100%	100%	100%	
S03	ZA0(AE)	100%	0%	0%	0%	0%	0%	EoL
	F04(MF)	100%	0%	100%	0%	100%	0%	
S04	ZA0(AE)	100%	0%	0%	0%	0%	0%	EoL
	F03(AG)	100%	100%	100%	100%	100%	100%	

S01 solutions are the baseline, where only the ETICS finishing layer is used, disregarding any other additional protection. The difference between S01_1, S01_2 (Min) and S01_2 (Max) lies in the maintenance: S01_1 assumes that, after the first application, every 10 years reapplication of this finishing layer to 50% of the exterior walls (north- and east-oriented walls, for example) is needed. S01_2 (Min) and S01_2 (Max) are variations of S01_1, where the former only considers a reapplication of the finishing layers in 25% of the walls and the latter a total reapplication of the finishing layer of the ETICS every 10 years.

The S02 solution consists of a traditional approach to protection with the use of biocides and hydrophobic products. A biocide is not a stand-alone product, as it needs to be diluted to derive the finishing layer, thus, it cannot be reapplied, as this solution does not consider the finishing layer's reapplication. It is considered that all the weathering only affects the outermost layer—the hydrophobic agent—therefore, only this layer needs to be reapplied. Considering that the hydrophobics have a service life of about five years, every five years they need to be reapplied on the whole façade of the building.

The S03 solution consists of the same ETICS finishing layer as the previous solutions, with the protection of a multifunctional product. This multifunctional product has an announced service life of 10 years. Thus, every 10 years it needs to be reapplied to all the outer surface of the building. As with the S02 solution, it is assumed that all the weathering only affects the outermost layer, thus the finishing layer does not need reapplication.

The S04 solution does not compete with the previous solutions, being a complementary protection for areas with potential graffiti problems. It should be used in parallel with the previous solutions. As the anti-graffiti product presents a service life of five years, it should be reapplied every five years, with the same assumptions as before: that only the outermost layer is affected by the weathering.

In Table 15, the results for the LCA and LCC are presented. These results consider the maintenance plans from Table 14 and the environmental impacts calculated before, and the LCC achieved with the calculations methods already described.

Table 15. Results for the environmental LCA and LCC.

Solution	PVLCC	ADP (ff)	GWP100a
	(EUR/m^2)	(MJ/m^2)	(kg eq CO$_2$/m^2)
S01_2 (Min)	12.66	61.22	5.96
S01_2 (Max)	23.66	122.43	11.91
S01_1	16.33	81.62	7.94
S02	26.95	53.99	5.27
S03	22.15	60.20	5.27
S04	34.44	114.40	10.64

Despite reaching values that can be considered reasonable, as with the maintenance interventions, a final decision is still not obvious. Thus, to facilitate a possible decision, a multicriteria analysis is needed.

This multicriteria analysis only compares the various solutions between themselves, apart from S04, which is the anti-graffiti solution, and that, obviously, does not compete with the other solutions in regard to function.

The multicriteria analysis consists of the attribution of weights to the environmental indicators vs. the economic indicator. It is considered that the environmental indicators always have the same weight, because, throughout this work, it was observed that ADP (ff) and GWP100a have some level of correlation. Therefore, for bad environmental solutions, both go up, and, in good environmental solutions, both decrease. Thus, it is considered here that the environmental weight is a function of the economical weight, that the ADP (ff) weight is equal to the GWP100a weight, and that both are equal to half of the environmental weight. First, the values reached in Table 15 are normalized into Table 16.

Table 16. Normalized results for the solutions.

Solution	PVLCC	ADP (ff)	GWP100a	Sum	Normalization
S01_2 (Min)	1.00	0.89	0.90	2.79	0.93
S01_1	0.74	0.60	0.60	1.94	0.65
S01_2 (Max)	0.23	0.00	0.00	0.23	0.08
S02	0.00	1.00	1.00	2.00	0.67
S03	0.34	0.91	1.00	2.24	0.75

With the normalized results, it was then possible to attribute weights to the three indicators considered in this study and see how the variation of the weights of the environmental and economic parts influence the best solution, as observed in Table 17. S01_2 solutions were ignored as these are not "real" but border solutions, best- and worst-case scenarios. Therefore, the average S01_1 solution was considered, but the other two were valuable for defining the spectrum of possibilities in which the values vary. As so, three solutions remained and, all of them, for certain combinations of weights, are the best solution.

Table 17. Effect of the variation of the economic weight vs. the environmental weight.

Weight PVLCC	1.00	0.90	0.80	0.70	0.60	0.50	0.40	0.30	0.20	0.10	0.00
Weight ADP (ff)	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
Weight GWP100a	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
S01_2 (Min)	1.00	0.99	0.98	0.97	0.96	0.95	0.94	0.93	0.92	0.91	0.90
S01_2 (Max)	0.23	0.21	0.18	0.16	0.14	0.11	0.09	0.07	0.05	0.02	0.00
S01_1	0.74	0.73	0.71	0.70	0.68	0.67	0.66	0.64	0.63	0.61	0.60
S02	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
S03	0.34	0.40	0.46	0.52	0.58	0.65	0.71	0.77	0.83	0.89	0.95
Colour code	🟩	Best solution (without S01_2)					🟦	Average solution (without S01_2)			
	🟧	Worst solution (without S01_2)					▒	Limit solutions (S01_2)			

S01_1 is the best solution in terms of cost effectiveness, from the point where cost is all that matters to a 50%–50% split between the weight of the economic and environmental indicators. The S03 solution is never the worst solution, and it is the best one when the PVLCC weight is in the [0.2; 0.4] interval and the environmental weight is in the [0.6; 0.8] interval. However, this solution is close to the first one in the [0.0; 0.5] interval, regarding the PVLCC weight. The S02 solution is the worst in terms of cost, but the best environmentally, being the best solution when the weight of the environmental indicator reaches the interval [0.9; 1.0].

4. Discussion

This study was developed with the objective of comparing, firstly, the different products on the Portuguese market within each type of product considered and, secondly, comparing concurrent solutions of protection for ETICS using a multicriteria sensitivity analysis.

According to the scope of the work, the main target was to compare products, however, when comparing the same types of products, it was chosen to present, when relevant, the most impactful components of each type of product.

To accomplish the aim of comparing the different solutions, the work began by collecting as much data as possible for the products available on the Portuguese market and then collecting their technical data sheets (TDS), safety data sheets (SDS) and, when applicable, their ETA.

Most products have a TDS, but many do not offer SDS through their website or customer service. As the most relevant information is disclosed in the SDS, the decision was made to disregard every and any product that did not provide this document.

However, most products with TDS and SDS have information deficits, not disclosing all components, their proportions, or their exact chemistry.

This information problem led to the development of an indicator, the information quality index (IQL), where the quantity, quality, and relevance of the information presented by the producers is quantified, allowing for the measurement of the quality of information.

Regarding the environmental information, its characterisation was achieved with the Ecoinvent V3 database. This presented another challenge, as the processes available in this software do not correspond perfectly to the products' components disclosed by the producers, so approximations were considered in this attribution of processes from the database to the known components.

However, through the consultation of an EPD of paints, it was possible to compare the results attained with the method of calculation described and with the final results of a similar product in the form of this EPD. This comparison allowed us to conclude that the results achieved through the approximations and calculation methods resulted in impacts within the same ballpark as the EPD. Therefore, the results achieved in this work are reasonable, and, with some careful analysis, there are important conclusions to retain.

Despite the results of the impacts assessment being reasonably accurate, it should be taken into consideration that the information available is less than ideal; nonetheless, the results presented appear to be good enough for comparisons between the products analysed (as the same considerations were assumed throughout the study), but more data required for more meaningful results.

In the multicriteria and sensibility analysis it was shown how the best solution varies according to the weight assigned to the PVLCC and environmental indicators. For a higher PVLCC weight, the use of only the finishing layer, with its reapplication on 50% of the outer surface of the building every 10 years, is the best solution due to the lower cost of the ETICS finishing layer. However, as the environmental weight gets higher and the PVLCC lower, until a 50–50 split, the S01_1 solution loses its relevance.

When the environmental weight reaches above 50% to 80%, the best solution is S03, that considers the ETICS finishing layers with multifunctional protection reapplied every 10 years.

If the weight of the environmental indicators is considered above 80%, the best solution is the S02, with the reapplication of the hydrophobic product every five years.

Considering all limitations encountered in this work regarding the quantity and quality of the information available, some further research should be conducted, mainly on the durability of these products (including the ETICS finishing layers); impact of protection products on the durability of the ETICS; evaluation of the ecotoxicity of the biocidal agents; studies on the durability of ETICS considering their maintenance in environmental and economical assessment; development of pragmatic methodologies to access the quality of information (like IQL); consideration of environmental indicators other than ADP (ff) or GWP100a.

5. Conclusions

This work tackles an area of knowledge with a yet small body of research. This is, within itself, a challenge, as methodologies on how to gather, process, and present information are difficult to implement considering the low amount of information available on the multiple products considered.

This work attempted to establish a ground base with a pragmatic set of rules/advice to categorize information through the IQL index, but the highly variable formats and quantities of information presented by the manufacturers, and the imprecise way in which they are presented are, in themselves, challenges to studies of this type.

The biocidal products, despite of their potential toxicity, have a very small impact on the ADP (ff) and GWP100a environmental indicators. There are two reasons for this result: first, these substances are highly regulated by ECHA, which controls the number of biocidal components that can be incorporated; second, the biocidal additives are used in small proportions, which vary from 1,25% to 10% of the paint by volume. Thus, biocidal products need to be studied in terms of their impact on the environment using other categories, particularly in terms of the toxicity of their leachates.

Multifunctional products, despite being present on the market, are still a relatively new class of products that lack variety of solutions and long-term studies that consider their exposure to the elements, their durability in harsh conditions, and other factors that contribute to their success or demise as a protection product in the building sector.

The environmental impacts of the anti-graffiti products are highly dependent on the number of cleaning cycles that are expected. Applying a sacrificial product in an area prone to vandalism results in very high environmental and economic impacts. In these products, the service life is important, but the recurrence of cleaning cycles is more important as a decision factor.

The development of a multicriteria analysis, where economic and environmental indicators can be conjugated according to perceived importance by the stakeholders, is central to a study like this one, improving the interpretation of results for all stakeholders and facilitating the comparison between solutions that greatly vary in terms of their economic and environmental impacts.

As shown, the "best solution" highly varies with the weights assigned to the PVLCC and to the environmental indicators. The pace of reapplication seems to be a relevant factor for the increase of the solution's cost, and the density (yield) of the product seems to affect more the environmental performance. The lower density, higher yield products seem to show better environmental performance, and the products with lower reapplication rates seem to show better PVLCC performance.

This equilibrium between cost and environmental impact shows the complexity of the decision process in construction; thus, the need to develop studies that compare different solutions in terms of their environmental and economic cost.

Defining the right indicators and the weight of each greatly impacts the ability to translate this work to real-life scenarios.

Better information is necessary: manufacturers must either disclose more information about the components of their products, or alternatively need to start providing environmental product declarations (EPD).

In following studies, problems such as toxicity, service life, and durability of the products and solutions can and should be considered to add to the body of knowledge and further facilitate the decision-making of stakeholders.

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