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A Framework of Unsustainable Behaviors to Support Product Eco-Design

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Abstract: Eco-designed products can contribute to sustainable development if consumers choose them rather than the less environmentally friendly alternatives and if they are used properly. However, eco-design methods have so far failed to address the issue of unsustainable behaviors, whose sources have not been recognized. In light of this deficiency, the authors have analyzed a large number of eco-designed products with the aim to capture the possible unsustainable behaviors arising from their use and consumption. The subsequent characterization of unsustainable behaviors has led to the creation of a framework of unsustainable behaviors, which has been subjected to the evaluation of a pool of experts in the field. In its final version, the framework includes nine classes of unsustainable behaviors, which are categorized into the corresponding product lifecycle phases (purchase, use, end of life), and different kinds of undesired effects (harmful, insufficient, excessive) based on the TRIZ-oriented functional analysis. The classes, whose significance has been checked in the literature, include frequent causes of unsustainable behaviors and corresponding examples. Through the framework, designers can take into due account the possible circumstances that would prevent their developed products from being prone to unsustainable behaviors. In a future step, the classes of unsustainable behaviors are to be linked with indications arising from Design for Sustainable Behavior.

Keywords: unsustainable behaviors; design for sustainable behavior; eco-design; design strategies; product development; product lifecycle; TRIZ; design requirements

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1. Introduction and Background

Eco-design supports designers in taking into account sustainable aspects during all phases of the products' life cycle [1]. However, a major criticality of eco-design is the real effectiveness of the developed sustainable products. Those often fail to satisfy customers' requirements and needs, and hence they do not truly contribute to sustainable development due to their scarce market penetration [2]. This has emerged clearly in a recent discussion held during the webinar organized on 30 September 2021 by the Design Society's Special Interest Groups "Sustainable Design" and "Design Process", which targeted the design science's contribution towards the United Nations' Sustainable Development Goal 12 "Responsible Consumption and Production". It was particularly highlighted that while design contribution to responsible production is evident and acknowledged, its support to the pursuance of sustainable consumption is questionable. Consequently, (eco-) design methodologies and science suffer from shortcomings when it comes to addressing the mentioned Sustainable Development Goal.

Markedly, mainstream eco-design methods tend to overlook factors that might jeopardize actual advantages in terms of sustainability [3–5] despite the potential goodness of eco-designed products (EDPs). Among those factors, the role of unsustainable people's behaviors can be mentioned. Taking into account the unsustainable behaviors (UBs) a person may exhibit or a product may be subjected to is critical to effectively developing

sustainable products. Markedly, human behaviors in relation to products can strongly influence (negatively) sustainable development [6]. As the present study addresses UBs displayed by users and consumers towards products, the focus is on people's actions that are currently not controlled or supervised by producers, manufacturers, and providers. These UBs and actions are here considered irrespective of the specific methods, principles, and strategies used to come up with the development of EDPs, such as Circular Economy, cradle-to-cradle or Product-Service Systems. It follows that the UBs considered here do not include designers', industrialists', and manufacturers' failure or reluctance to adopt proven models and methods for sustainable development. The boundaries of studied UBs will be further clarified in Section 2.1.

In this context, various studies on how to steer users' behaviors have been conducted. Therefore, designers and researchers have started to focus on Design for Sustainable Behavior (DfSB), which may be addressed as a complementary thread with respect to eco-design [7]. Several sources [8–14] document the triggers of development, outreach, diffusion, and theoretical background of DfSB, along with approaches sharing the same goals while possibly differing in terminology.

According to [6], DfSB targets the design of solutions that, not only exhibit a lower environmental harmfulness, but also prompt modifications of perspective users' interactions with the developed products, which results in modifying their behavior towards sustainable goals. In other terms, DfSB does not simply focus on the environmental impact of products, but also aims to understand how and why that product might affect the sustainable habits of a consumer. In this area of research, a tenet is that modifying consumers' behaviors through design is viable. Consequently, conceptual studies mostly focused on the illustration of strategies for steering behavior changes.

According to [10], strategies for DfSB investigate possible behavioral changes by means of different frameworks, namely schemes and methodologic drivers to understand and categorize sustainable behaviors. A variety of frameworks are available in the literature and an overview of the salient concepts is useful for the scope of this paper. A firstly introduced approach [7] based the induction of sustainable behaviors on the adaptation of behaviors and the specific design to trigger sustainable use. The framework they developed presents three strategies characterized by different magnitudes of intervention to steer sustainable behaviors: (i) Feedback, providing consumers with information about the environmental consequences of their behaviors; (ii) scripting products to induce sustainable use; and (iii) forcing, in order to avoid unsustainable behaviors. Overall, the most notable frameworks for DfSB focus on this three-strategy set, differing primarily in terms of terminology, granularity level, outreach of the strategies, and explanations provided to illustrate what the strategies include. For instance, strategy (iii) is redefined as persuasive technology in [15], which tends to change customers' behaviors, sometimes without their full consent or awareness. The authors in [16] establish phases to inform, maintain, and force the change [12], similarly to [7]. A further expansion of this framework can be found in [17], which proposes a subdivision of the three main strategies, according to the user's power in decision-making. The authors in [8] propose a slightly different framework, which has the scope of influencing and forcing sustainability in users' behaviors based on eleven strategies. Other and more recent attempts of developing different frameworks can be found in [18,19], but the common thread is simply represented by proposing and classifying actions, practices, measures, and principles to make people's behavior more sustainable.

Although DfSB is well established to indicate how to induce sustainable behaviors as stated in various review papers [10,12], some research gaps can still be found, especially when it comes to capitalizing on DfSB knowledge in eco-design.

The mentioned adherence to the three-strategy framework calls into question the comprehensiveness of the presented DfSB approaches. Otherwise said, as the developed models have been substantially based on a reference framework, it can be questioned whether the three strategies along with their expansions and specifications can address all possible problems in terms of UBs due to the use, possession of, and interaction with

products. This limitation might then result in missing design principles to steer customers' behaviors in a number of circumstances.

An additional weakness is represented by the lack of guidance in the use of DfSB strategies in a product design process. The starting point for the application of DfSB strategies is rather a psychologic trigger or need in some cases, e.g., [20]. Most of the contributions in the area of DfSB provide brilliant examples of design changes viable to change people's behaviors and possibly reduce the environmental footprint. No process has been developed that logically links a problem to solve or a requirement to fulfil with principles, methods or approaches [6], which are necessary steps in design processes and product development. On the one hand, this calls into question effectiveness issues, as DfSB strategies are consequently applied unsystematically. In this regard, many authors additionally claim the severity of these problems and the simultaneous lack of studies to verify the real effectiveness of DfSB strategies adopted, e.g., [21]. The problem is partially alleviated when DfSB approaches are applied in User-Centered Design tasks, e.g., [22–24], since individuals are more directly involved in the design process. On the other hand, the limited guidance shown by DfSB in design processes highlights the need to identify and define which problems can be actually solved with the strategies and suggestions included in the above frameworks. These strategies seem of general applicability and have the overall ambition of educating people towards being sustainable and acting sustainably. Therefore, it is unsurprising how many DfSB examples deal with the systems used and handled by public institutions to push the adoption of environment-aware, respectful, and healthy behaviors, see, e.g., the examples provided in [25]. However, less is known about the strategies' appropriateness to correct or prevent the misuse of products and consumer goods with negative environmental consequences, which might be largely the result of poor awareness or knowledge of what is actually more sustainable [3], wrong perceptions [26] or unwitting actions. In this respect, it emerges how the identification and characterization of UBs may represent the stepping-stone to a better integration of DfSB in (eco-) design.

The need to consider UBs beyond inducing sustainable behaviors is specifically stressed in [10], which identifies this aspect as a relevant weakness in DfSB research. The authors in [27] highlight the issue of identifying conditions for unwanted behaviors. In [28], the authors point out that enhancing sustainability within customers' actions should also primarily consider what is sustainable and unsustainable in an action. This aspect underlines the need for a thorough understanding of UBs and how those can be identified in the design process in order to apply DfSB strategies or new (eco-) design principles. The construction of a comprehensive framework of product-oriented UBs useful to design is the objective and main result of this paper.

2. Materials and Methods

In the present section, the process behind the development of a framework to classify UBs is presented. This framework, whose final version is presented in Section 3, has been developed and fine-tuned through multiple steps as illustrated in Figure 1, which clarifies the inputs and outputs of these different steps. First, the phases of the product life cycle where people's behavior could potentially be unsustainable were identified (Section 2.1). Second, the authors examined (in a brainstorming session) the potential criticalities (in terms of the effects of unsustainable behavior) of the EDPs described in [29]. The outcome of the brainstorming session has resulted in a preliminary framework that, in turn, has been evaluated by six eco-design experts (Section 2.2). The preliminary framework was modified based on the feedback received, and a final framework was then proposed (Section 2.3). This final version was evaluated by the same six eco-design experts. The feedback showed unanimous agreement in the framework's ability to comprehensively and consistently cover the various UBs a person may adopt and/or a product may be subjected to accordingly.

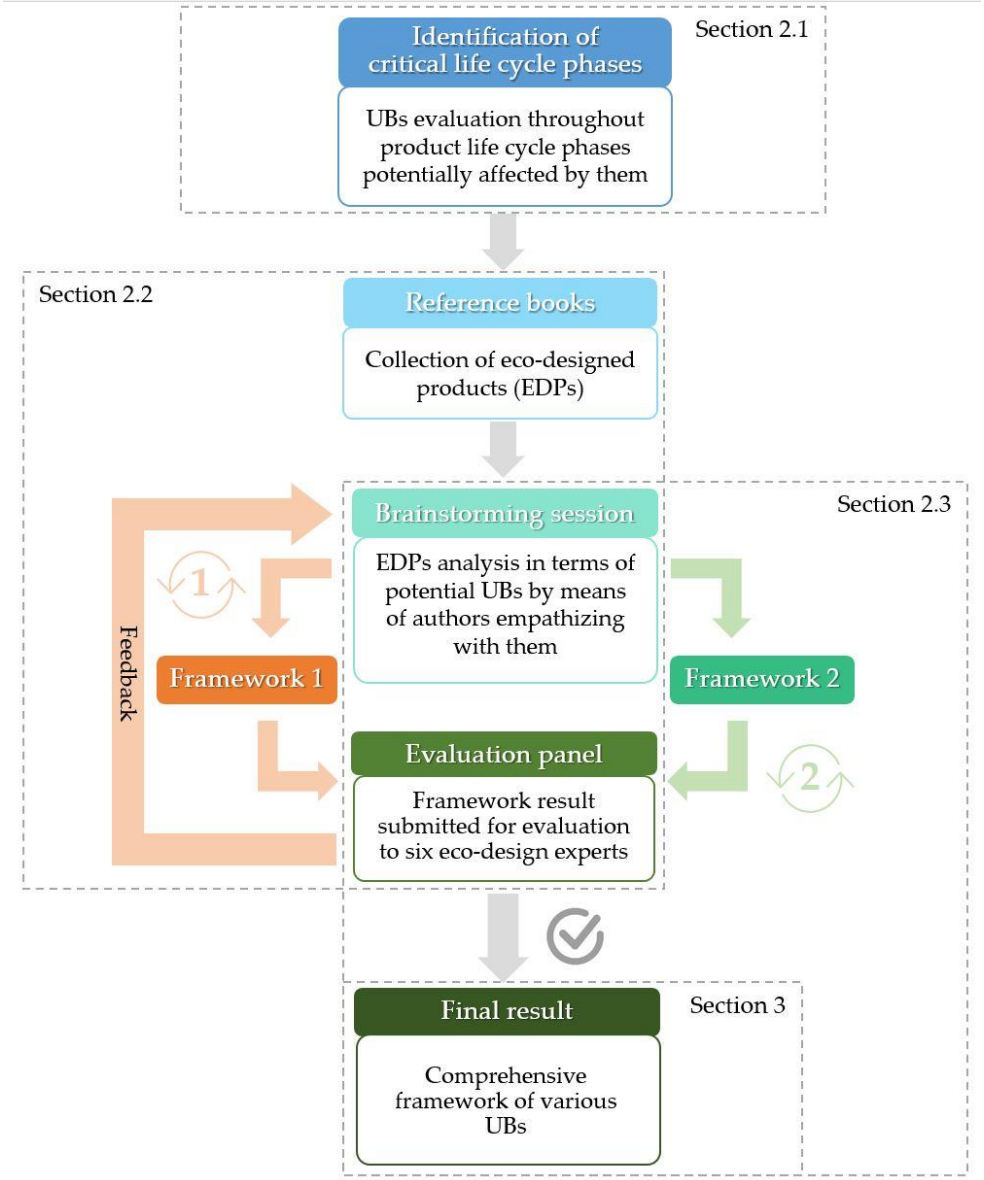

Figure 1. Methodological approach followed in the research.

2.1. Identification of the EDP Life Cycle Phases Where People's Behavior May Prove to Be a Barrier to the Expected Sustainability

In relation to the different product's life cycle phases, i.e., pre-production, production, distribution, use, and end-of-life (EOL), it is possible to identify when people's behavior could directly affect the EDP sustainability. The relevance of use and disposal are straightforward. People, markedly users or consumers, can use an EDP in a different way from the designed (optimal) one by actually misusing it. Therefore, if it occurs, the sustainable benefits potentially enabled by a new design are jeopardized [30]. On the other hand, with respect to the EOL phase, people could not dispose the EDP as required. Therefore, in this case, all of the potential environmental benefits from material selection and/or reusing, remanufacturing, recycling or composting processes are jeopardized [31]. In addition to use and EOL, numerous studies emphasize that the concept of sustainability necessarily includes the market success [3–5,9]. Indeed, an EDP that is not purchased (or exploited in case of service) cannot be considered sustainable [32]. In other words, a consumer could not purchase the EDP due to the fact that they prefer a less sustainable alternative to the EDP in question. Regardless of the reasons behind this consumers' choice, it is indisputable that, if an EDP is not purchased, all of the potentially sustainable advantages conceived during de-

sign are ineffective. Therefore, since the purchase phase is a fundamental step (influenced by people's behavior) in determining the diffusion of the EDP, the authors considered it appropriate to add a further phase in the classic life cycle, i.e., the purchase phase.

Eventually, the EDP life cycle phases where peoples' behavior may be a barrier for achieving the expected sustainability are purchase, use, and EOL (Figure 2). The other phases, i.e., pre-production, production, and distribution, can be considered disjointed with respect to the people's behavior, since these phases are fully managed by design, production, and logistics.

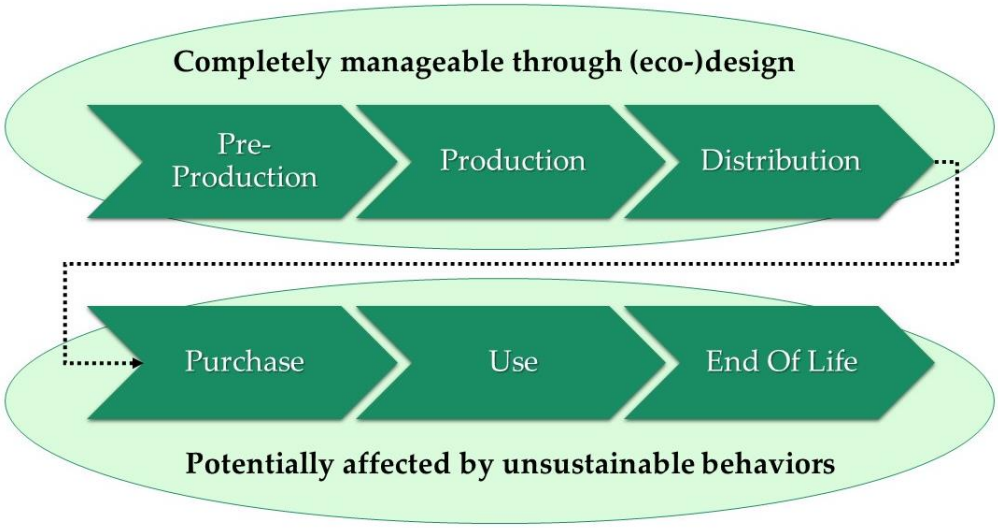

Figure 2. Life cycle phases potentially affected by unsustainable behaviors.

2.2. Preliminary Characterization of Unsustainable Behaviors and Expert Evaluation

"Design for environmental sustainability" [29] is a pillar reference in the sustainable- and eco-design field. In this book, many EDPs have been illustrated to elucidate eco-design strategies and principles. However, although these products are good examples for the book's objective, they are not exempt from being affected by UBs. For instance, the Ikea air sofa has been exploited by the scholars as an illustrative example of dematerialization. However, it is acknowledged that this product was a fiasco [3]. On the same line, the scholars promote the car sharing as use-oriented eco-efficient Product-Service Systems. However, it is established that the user behavior has a determining role on the actual sustainability of the car sharing system, especially when it is preferred to public transport rather than the private car [33]. Therefore, the authors, during several brainstorming sessions, analyzed all of the products and eco-design examples shown in [29] and hypothesized reasonable UBs (and their causes) that might arise. In particular, the authors attempted to emphasize with products and played the role of users (lacking discipline and sustainability awareness). Therefore, the approach mirrored the persona model, frequently used in experience-based and sustainability-oriented design [34–36], markedly in the task of elucidating design requirements [37]. Here, the search for requirements had a limited focus on the product characteristics and circumstances that could engender UBs.

The UBs that emerged in the brainstorming sessions were abstracted and categorized according to the three stages of the life cycle. The result of this process led to the framework summarized in Appendix A. This framework has been sent to six eco-design experts from five different countries. The involvement of experts to evaluate classifications and lists of items for scientific purposes is the main milestone in research studies, as shown in [38]. In this study, the experts were invited to comment on this classification, especially in terms of those metrics that are critical to evaluating taxonomies based on the literature [39,40], markedly:

- Comprehensiveness, i.e., the capability of the classification in terms of covering the possible situations in which UBs dealing with products can be spotted;
- Consistency, coherence, i.e., the robustness of the classification, the extent to which the subdivision between classes is understandable and reasonable;
- Non-redundancy, i.e., the extent to which the classes do not overlap;
- Clarity.

Moreover, the evaluators have been urged to comment with respect to other issues they might have wanted to bring to the authors' attention.

All of the evaluators highlighted the originality and usefulness of classifying UBs for design scopes, but raised some concerns on the structure and the presentation of the first-attempt classification. Specifically, they highlighted that:

- With respect to comprehensiveness, the preliminary framework was not able to clearly capture the misuse of the product (intentional or unconscious). Moreover, the level of granularity of the preliminary framework has been questioned, since it was not able to cover UBs that could be manifested with services or Product-Service Systems;
- In terms of consistency and coherence, some terms adopted in this framework were evaluated as neither clear nor derived from systematic categorization. Moreover, it has been pointed out that the rebound effect is not a behavior, but a negative outcome of a behavior;
- Some classes resulted as insufficiently clear and others as partially overlapping. Moreover, adding practical examples to improve clarity was suggested.

2.3. Fine-Tuning of the Final Framework

Based on the raised criticism and specific suggestions provided by the eco-design experts, the framework was fine-tuned. First, a systematic method to characterize the undesired effects of the UBs has been applied. With this respect, the functional analysis proposed in the TRIZ methodology [41] has been exploited. TRIZ is the Russian acronym for the "Theory of Inventive Problem Solving" and, in practice, the TRIZ methodology proposes a series of tools for the identification and creative resolution of problems. The concept behind the functional analysis (as understood in TRIZ) is that different parts of a system interact through functions. The main goal of the system is to fulfil the main useful function. However, when a problem arises, other kinds of functions/effects are present. The undesired effects, such as UBs if a person is part of the analyzed system, can be classified in the following three groups, e.g., [42,43]:

- Harmful effects: Undesirable effects that adversely modify the system parameters;
- Insufficient effects: Effects that change the parameters of the system in the right direction but do not reach a satisfying threshold;
- Excessive effects: Effects that modify the parameters of the system in the right direction but in an excessive way. Therefore, this potentially generates new problems within the system or with different systems.

The new framework has been formulated by benefiting from the above categories of effects to target consistency, coherence, comprehensiveness, and non-redundancy. Therefore, this categorization has been added to the lifecycle considerations. Moreover, the classes achieved from the combination of lifecycle phases and categories of effects have been checked in terms of their actual relevance in the literature. The classes were enriched by possible causes of UBs in order to help identify the possible relevance of certain UBs for a product to be designed. Furthermore, the new framework has been enriched by explanatory (practical) examples to improve clarity, as suggested by the experts.

The final framework has been evaluated by the eco-design experts involved in the previous step. The structure of the framework along with the examples have been provided through a slideshow presentation. Based on the received feedback, no further changes to the classification and its presentation were requested.

3. Results: A Framework of Unsustainable Behaviors for Designs

The UB classes and reference framework that emerged from the process described in the previous section is shown in Figure 3. In the figure, it has been emphasized that several barriers hinder the achievement of the level of sustainability envisioned in eco-design. The phases following the production and distribution processes where people's behavior can play a relevant role are purchase, use, and EOL (top of Figure 3). Moreover, in the phases prone to be affected by UBs, those can be classified according to the three types of undesired effects based on TRIZ (harmful, insufficient, and excessive), as highlighted in the left-hand side of the figure. The above-mentioned combination (relevant life phases and TRIZ undesired effects) gave rise to nine independent classes comprehensively categorizing different barriers to sustainability due to UBs. A more detailed description of these classes (potential causes of UBs are presented) is provided in the subsections included in Sections 3.1–3.3, where references indicate examples of UB categories and causes. Each of these subsections reports a class of UBs with the same description administered to the experts in the second (and final) evaluation round.

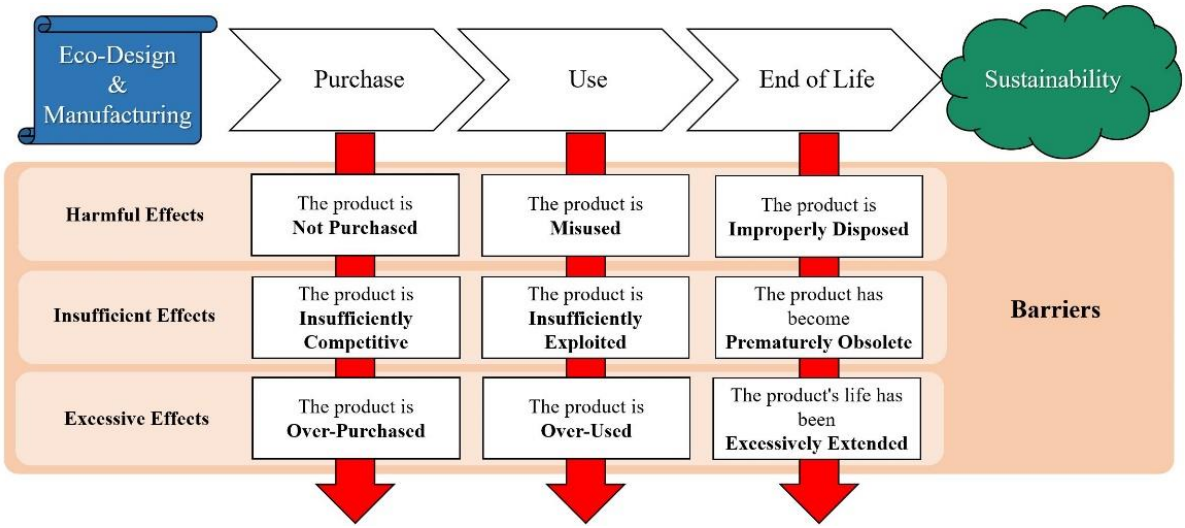

Figure 3. Proposed framework for mapping unsustainable behaviors affecting (eco-designed) products.

3.1. UBs Potentially Emerging during the Purchase Phase

3.1.1. The Product Is Not Purchased

The product could be not purchased, since the consumer prefers a less sustainable alternative to the product in question. The EDP is not (re)purchased, since the consumer does not perceive (has not perceived) its value and it can be considered a market failure. This may be due to the fact that the EDP does not achieve specific performance thresholds or it requires resources (in terms of time, money, space or information) that the consumer is not willing to sacrifice [44]. For example, the time required to refill a simple and cheap item such as a glue stick is not worthwhile in the user's view. One additional example can be related to edible packaging. Consumers can be aware of reducing waste. However, hygiene issues might be perceived by the users, as well.

The possible causes for this UB are listed below and additional details can be found in Appendix B, Table A4.

- The EDP exhibits missing or insufficient performances [45,46];
- Additional time is required by the user, e.g., consumers need to learn how the EDP works or should be used [47];
- Costs are excessive [48,49];
- The use or purchase of the EDP is bothering to some extent [45];
- New knowledge or skills have to be acquired and habits have to be changed [50,51].

3.1.2. The Product Is Insufficiently Competitive

The consumer buys the EDP. However, the EDP fails to replace the purchase (and therefore the use) of (at least) an alternative less sustainable product. This may be due to the fact that the EDP does not achieve specific performance thresholds. It can be considered a niche product or a product that replaces the less sustainable alternatives on a limited number of occasions only. A possible cause can be the lack of performances or presence of any issues that do not enable the full substitution of less sustainable alternatives [52,53]. For example, the manual washing machine or the solar cooker are two clear examples targeted by eco-design books that have not replaced traditional washing machines or cookers in peoples' life. Additional examples and clarifications on this category can be found in Appendix B, Table A5.

3.1.3. The Product Is over Purchased

The consumer buys the EDP, which is competitive with less sustainable alternatives. However, the superior performances of the EDP induce consumers to buy it even if they "do not need" it or they "do not need" an excessive quantity of it. A classic example exploited in eco-design books is the Lush solid shampoo, i.e., a shampoo that can be transported and used without packaging. The product is sustainable (reduced packaging) and original, and, as such appropriate for gifts. Therefore, when it is sold for gifts, a different kind of packaging and additional gadgets are usually included. An additional example can be related to 3D printing technologies. These enable a high level of customization with low material consumption. However, while they have become increasingly accessible, people have overexploited them by requesting objects that were not actually necessary. Two possible causes of this class of UBs are presented below and further details are provided in Appendix B, Table A6.

- Over purchase due to the high quality/price ratio of the EDP [54];
- Over purchase due to the creation of newly induced needs of the EDP [55].

3.2. UBs Potentially Emerging during the Use Phase

3.2.1. The Product Is Misused

The sustainable benefits potentially enabled by a new design are jeopardized in the fact that the user uses the EDP in a different way from the designed (optimal) one. An example may be related to concentrated detergents. They are considered more sustainable since they provide the same performance with decreased material use. However, it has been observed that many users tend to use the same amount of detergent they were used to (despite the fact that less would be sufficient). Overall, the possible sources of misuse are listed below, while support examples are reported in Appendix C, Table A7.

- The EDP is misused due to the lack of control and/or the user ignores the correct way of using it [56,57];
- The EDP is not correctly maintained [58];
- The EDP is misused due to being employed in the wrong context or for functions that it is not intended to perform [56,57].

3.2.2. The Product Is Insufficiently Exploited

The EDP fails to replace the use of (at least) an alternative less sustainable product or it is not exploited as expected when designed. For example, the iPod and MP3 players are often used as examples of dematerialization since they are able to contain the same hours of music that was previously contained on many CDs. However, these electronic devices have been used for a too limited time (due to the introduction of smartphones) to justify the substitution of previously used products. Their usage was too limited in time to be justified in terms of sustainability. The causes of this UB are listed below and additional clarifications can be found in Appendix C, Table A8.

- Although the more sustainable product could be used in specific circumstances, the user keeps preferring a less sustainable alternative in some conditions [59];
- The users' needs get changed and/or they can be fulfilled in new ways and the EDP is not sufficiently exploited [60].

3.2.3. The Product Is Overused

The superior performances of the EDP induce the consumers to use it even if they "do not need" it to such an extent. For example, LED lightbulbs have a much lower energy consumption than the incandescent bulbs. Therefore, they can be kept switched on for longer times than needed, as the user is aware of their limited energy consumption. Another example can be related to the car sharing services, which are services providing a shared car fleet to customers, who pay for the kilometers of travel, for the time of use or for a mix of the two. Therefore, the car owner has an economic interest in providing efficient and non-polluting cars. In this case, users can benefit from this service rather than public transportation based on the advantages it provides, e.g., entering the town center. Overall, the possible causes behind the overuse are summarized below and additional examples can be found in Appendix C, Table A9.

- Overuse due to the perception of the low cost of the resources necessary for the operation of the EDP [61];
- Overuse due to the high quality/price ratio of the EDP [62].

3.3. UBs Potentially Emerging during the End of Life

3.3.1. The Product Is Improperly Disposed

The user does not dispose the EDP as required. Waste management policies are very important for sustainability. However, the disposal policies are not the same in every region/city. There are different disposal regulations for every region/city. When people are not informed clearly, they might not act as desired due to the lack of knowledge or their habits. In Appendix D, Table A10, the explanatory examples for this UB are reported.

- The product is difficult to be disassembled and materials cannot be easily separated [63];
- The user ignores or overlooks the correct way of disposing products [31,64,65].

3.3.2. The Product Has Become Prematurely Obsolete

The EDP (or part of it) is discarded prior to the end of its useful (expected and/or technical) lifetime. For example, users might tend to substitute their PC prior to the end of its useful life, since they are attracted by rapidly increasing performances. The possible causes for this UB are listed below; additional clarifications can be found in Appendix D, Table A11.

- The product is perceived to be no longer competitive in terms of its technical performance [66–68];
- The product is perceived to be no longer competitive due to the changing (social) trends, fashion, and consumers' preferences [69,70].

3.3.3. The Product's Life Has Been Excessively Extended

The EDP is not replaced by the latest eco-designed alternatives despite being obsolete. This may be due to the fact that the consumer is attached to the outdated EDP or due to the fact that buying a new EDP would require (monetary) resources that the consumer is not willing to sacrifice. For example, although a twenty-year-old car was designed following the eco-design guidelines of that time, it is not necessarily more sustainable than any car produced nowadays. It would be wise to change it if the overall impact suggests that. The users could get attached to their car and be reluctant to change it even it is no longer convenient from an environmental perspective. As a possible cause for this UB, the consumer is attached to the outdated product or would require (monetary) resources that

they are not willing to sacrifice [71,72]. In Appendix D, Table A12, additional information is reported.

4. Discussion and Conclusions

4.1. Main Findings and Comments

Disregarding the possible effects of users' behavior in product development can jeopardize design efforts, especially when sustainability is dealt with. It is of anecdotal evidence that the misuse, mishandling or mismanagement of a product can cause undesired effects, such as harming the environment. Therefore, this issue is particularly relevant when eco-design processes are in place. Here, overlooking the fact that people are part of the system the product is integrated in can lead to unintended consequences and jeopardize the efforts made to sustainable product development. Actually, in a typical design process oriented to product development, the designer is expected to fulfil the previously identified requirements. If the requirements are not elicited, a design process, although carried out appropriately, cannot give rise to satisfactory outcomes. In this paper, the authors stress the need to consider the avoidance or minimization of UBs as part of the definition of design requirements. This is favored by the presented framework of UBs. A designer can actively use the framework as a checklist to identify which UBs the product under development can be subjected to. It is worth stressing that the creation of the framework proposed in this work represents the main original contribution of the present research. To the authors' best knowledge and state-of-the-art analysis, similar attempts to focus on and classify UBs for design purposes have not been made. Therefore, the authors lack any reference to compare the paper's findings with previous contributions.

The framework can be considered the missing link between the (eco-) design process and DfSB methods. Indeed, as pointed out in the introduction, DfSB methods tend to propose solutions without systematically supporting problem analysis. Through the proposed framework, the analysis of problems potentially arising due to UBs is systematically supported. In addition, from an educational perspective, the framework is useful for understanding the limitations of eco-design when UBs are in play. Through this framework, barriers in existing solutions can be highlighted and new design challenges can be formulated.

While the main benefits arising from the development of the illustrated framework of UBs lie in the design field, the general understanding of UBs related to products clearly represents a contribution beyond design. Overall, all of the disciplines potentially dealing with UBs can benefit from the presence of a framework, classification or taxonomy that have undergone a validation process. In particular, while the field of DfSB has been seldom subjected to studies investigating the exhaustiveness of related concepts, e.g., principles and strategies, the authors have targeted the achievement of a comprehensive framework. The capability of DfSB strategies to cope with the UBs elucidated in the present paper will represent a possible litmus test for DfSB comprehensiveness.

4.2. Limitations and Future Work

The connection between classes and causes of UBs (seen as potential problems) and design principles addressing them is indeed the most important future work envisioned by the authors. A current limitation of the present work is actually the fact that the framework currently supports the identification of significant issues related to (eco-designed) products, but no means for overcoming them are provided. Therefore, future research will be conducted to identify suitable design actions in relation to people's behavior, thus largely following in the footsteps of [73].

Other future research and limitations are worth mentioning. As for the former, the authors are willing to use their findings to consider the potential impact of UBs onproducts' environmental assessments. Markedly, Life Cycle Assessment, seen as a reference for systems' environmental sustainability, is criticized for its limited consideration of how humans might affect it [74]. Moreover, a potential new field of study opened up by the

present research is represented by the investigation of alternatives to DfSB in addressing design problems related to UBs. In this respect, a possibility is represented by TRIZ, which, in addition to its acknowledged problem-solving capabilities, has proven effective in categorizing UBs. Moreover, it is worth noting that TRIZ originates from the engineering field, but its use is increasingly common for problems involving environmental sustainability, value aspects, and the humanities in general [44,75–82], which represent a clear reference for this study.

With regards to methodological limitations, it has to be pointed out that the procedure to verify the framework is affected by subjectivity despite the attempts to implement standards for scientific validation. This is unfortunately common to all the processes where human judgement is involved. Eventually, a content-oriented limitation can be viewed in the current failure to include the magnitude of negative effects produced by the different classes of UBs in the study. As design requirements are often prioritized in design tasks, it would be useful to understand whether some classes or causes are to be targeted first. Nevertheless, following the TRIZ classification of undesired effects, it can be hypothesized that harmful effects can also be the most detrimental in the domain of UBs.

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Appendix A. Preliminary Framework

Table A1. Preliminary framework related to the barriers that could be manifested during the purchase phase.

Category of Unsustainable Behavior	Definition	Illustrative Examples, Additional Explanations, Typical Causes
Missing value aspects	The consumer might be tempted to relinquish the purchase of the product because some expected benefits are not delivered by the product or are not perceived as such	Scepticism about the product's capability of delivering some benefits; questioned integrity of the product, for instance during transportation in case of reduced packaging
Need for sacrifice	The consumer might be tempted to relinquish the purchase of the product because some sacrifices are needed or perceived as such	Excessive costs; long-term agreements to be met; additional operations to be carried out
Difficulties to identify value	The consumer might be tempted to relinquish the purchase of the product because advantages are unclear or require a change of habits	Design modifications are not made sense of; advantages, including those in sustainable terms, cannot be figured out

Table A2. Preliminary framework related to the barriers that could be manifested during the use phase.

Category of Unsustainable Behavior	Definition	Illustrative Examples, Additional Explanations, Typical Causes
Use of excessive material or energy (product itself)	The sustainable benefits ensuing from design are jeopardized in that the user uses excessive material (in case of consumable products) or energy	The product is not used in the energy-save mode; the amount of the consumed product exceeds the real necessities, for instance due to previous habits
Use of excessive material or energy (auxiliary)	The sustainable benefits ensuing from design are jeopardized in that the user uses excessive additional auxiliary materials or resources to make the product work	The product is not used in a way that minimizes the consumption of external supplementary consumables; the user buys unneeded accessories
Rebound effects; overuse or over-purchase	The user is aware of the product's superiority in terms of sustainability/cheapness and tends to overuse it or buy it in a larger quantity	The product engenders over-induced needs; the product is used more frequently than necessary, which can jeopardize previously more sustainable habits
Lack of maintenance	The user does not carry out planned or needed maintenance	The maintenance activities are cumbersome and considered not worthwhile

Table A3. Preliminary framework related to the barriers that could be manifested during the end of life phase.

Lack of incentive for not buying an alternative product	The experience with the product does not prevent the purchase of less sustainable alternative products	The user is not satisfied with the product and interrupts its use; the product becomes obsolescent, for instance in terms of fashion trends; the user does not get used to changing their habits to benefit from the product adequately
Unexploited product duration	The product is discarded prior to the end of its useful life	The product is discarded because of unexpected sacrifices, lack of comfort or convenience, obsolescence, unwillingness to change habits
Wrong disposal	The user does not dispose the product as required	The product is difficult to be disassembled and materials cannot be easily separated; the user ignores the correct way of disposing products
No repurchase	The user does not repurchase the product	The product is not repurchased because of unexpected sacrifices, lack of comfort or convenience, obsolescence, unwillingness to change habits; the user is not satisfied and prefers previously experienced (and less sustainable) alternative products

Please notice that the term "product" is used in this appendix in a broad sense and includes artefacts, tangibles, services, product-service-systems or other outcomes of design processes.

Appendix B. Unsustainable Behaviors That Could Be Manifested during the Purchase Phase

Table A4. Examples for clarifying the candidate causes of unsustainable beahavior when the product is not purchased.

Candidate Causes of Unsustainable Behavior	Example	Reasons behind the Product Sustainability	Possible Reasons behind the Unsustainable Behavior
The EDP exhibits missing or insufficient performances.	Edible packaging	Packaging that is designed to be eaten or has the ability to biodegrade efficiently like the food that it contains.	The consumer can be aware of reducing waste, however hygiene issues might be perceived by the user as well.
Additional time is required by the user, e.g., consumers need to learn how the EDP works or should be used.	Refillable glue stick	The mechanism can be used permanently by changing the tape.	The time required to refill a simple and cheap item such as the glue stick is not worthwhile in the user's view.
Costs are excessive.	Whirlpool Green Kitchen	A futuristic design that proposes to reduce water and heat consumption.	Not only this green kitchen was too expensive, but it required accessory costs.
The use or purchase of the EDP is bothering to some extent.	FRIA by Ursula Tischner	A fridge that uses cold outside air in order to reduce energy consumption.	The kitchen and room should be fully rearranged.
New knowledge or skills have to be acquired; habits have to be changed.	Beauty Kitchen Return-Refill-Reuse	The consumer is responsible with returning product (the container) so that the company can re-use it and reduce waste.	The consumer might prefer another product because of lack of confidence to use and manage the system as required.

Table A5. Examples for clarifying the candidate causes of unsustainable beahavior when the product is insufficiently competitive.

Candidate Causes of Unsustainable Behavior	Example	Reasons behind the Product Sustainability	Possible Reasons behind the Unsustainable Behavior
Lack of performances or presence of any issues that do not enable the full substitution of less sustainable alternatives.	Car pooling, e.g., Bla Bla Car	It is a mode of transportation that consists of sharing private cars among a group of people, with the main purpose of reducing transportation costs and environmental impact.	The user knows that it is better to share the journey in terms of environment and costs, but previous delays and bad experiences with unknown people the journey has been shared with make users refrain from diffusely benefitting from car pooling.
	Mechanically powered products, e.g., flash lights, trimmers or hand-tools	These tools use hand power instead of batteries. These EDP are required to be powered before using (In general, with low usage time or performance).	Mainly technical aspects might drive the consumer to purchase a less sustainable product as well.
	Solar cooker	A cooker that works with the solar power instead of gas.	Limited usage time could lead the customer to the less sustainable (more traditional) alternatives.

Table A6. Examples for clarifying the candidate causes of unsustainable beahavior when the product is over-purchased.

Candidate Causes of Unsustainable Behavior	Example	Reasons behind the Product Sustainability	Possible Reasons behind the Unsustainable Behavior
Over purchase due to the high quality/price ratio of the (eco-designed) product	3D printing services	Additive manufacturing technologies enable a high level of customization with low material consumption.	While they have become increasingly accessible, people have overexploited them by requesting objects that were not actually necessary.
	Dopper Bottle Water	Reusable water bottles made by plastic, glass and steel in order to reduce the single used plastic water consumption and promoting the tap water usage.	Due to its advertisements, accessibility, and product range, one might want to have more products than actual requirements.
Over purchase due to the creation of newly induced needs of the eco-designed product	Lush solid shampoo	Solid shampoo so that a traditional packaging is not necessary.	The product is sustainable (reduced packaging) and original, and, as such appropriate for gifts. When sold for gifts, a different kind of packaging and additional gadgets are included.
	Electric pushed scooters	In many cities, electric pushed scooters are considered as fundamental for the sustainable mobility since they help reduce cars exploitation.	There have been initiatives that have pushed their purchase, which have resulted in replacing the use of bicycles and public transportation, and walking habits rather than cars.

Appendix C. Unsustainable Behaviors That Could Be Manifested during the Use Phase

Table A7. Examples for clarifying the candidate causes of unsustainable beahavior when the product is misused.

Candidate Causes of Unsustainable Behavior	Example	Reasons behind the Product Sustainability	Possible Reasons behind the Unsustainable Behavior
The EDP is misused because of lack of control and/or the user ignores the correct way of using it	Concentrated detergent	Concentrated detergents are considered more sustainable because they provide the same performance with less material use.	The user uses the same amount of detergent they were used to despite less would be sufficient.
	Detergent-saving washing machines	Detergent-saving washing machine can have the same performance with a lower use of detergent.	The user uses the same amount of detergent they were used to despite less would be sufficient.
	Enviro systems E-cloth	The E-cloth System is a housecleaning cloth that, thanks to special microfibers, cleans the surfaces (of glass, stainless steel, chrome steel, etc.) without chemical detergents.	Although the product can work without any additional materials (solvents, detergents), consumers might still use those due of habits or because they believe additional materials enable superior performances.
	Items integrating solar chargers	Solar-powered phone charger allows you to use 100% solar energy to recharge electronic devices instead of the energy produced from other sources.	The user might fail to load the charger with its solar power option; instead, they prefer traditional ways of recharging devices.
The EDP is not correctly maintained	ADBlue	Although the necessity of an additional material usage is open to discussion, the company claims that it is effective on reducing CO_2 emission.	The solvent reduces CO_2 emissions, but if not regularly refilled by drivers, the car usage gives rise to severe environmental problems.
	Solar panels	Solar sourced systems require maintenance in order to keep the efficiency.	Sustainable advantages are not achieved if maintenance is not performed correctly.
The EDP is misused because of being employed in the wrong context or for functions it is not intended to perform	A+++ household appliances	High performance households, for example white goods, and claim less energy consumption on specific operation.	The user might tend to employ them in wrong circumstances, also due to their convenience, e.g., heating a plate in the oven.

Table A8. Examples for clarifying the candidate causes of unsustainable beahavior when the product is insufficiently exploited.

Candidate Causes of Unsustainable Behavior	Example	Reasons behind the Product Sustainability	Possible Reasons behind the Unsustainable Behavior
Although the more sustainable product could be used in specific circumstances, the user keeps preferring a less sustainable alternative in those conditions	Hybrid Cars	The vehicles that have the option to use fossil fuel or electricity.	The user limits the use of electric cars to downtown travelling, but they keep using fuel cars for longer journeys.
	Water filters and purifiers	Filtration systems that allow the user to filter or to purify the tap water instead of getting bottled water.	The user might keep purchasing bottled water instead of using filtered tap water, for instance when they want to drink water with gas, in presence of guests (offering tap water is impolite in some countries).
The users' needs get changed and/or they can be fulfilled in new ways and the EDP is not sufficiently exploited	Electronic dictionary	The electronic dictionary is often used as an example of dematerialization because it is able to contain the same information that was previously printed on many kilograms of paper.	These electronic devices have been used for a too limited time (because of introduction of smartphones) to justify the substitution of previously used sustainable products. Their usage was too limited in time to be justified in terms of sustainability.
	iPods and MP3 players	The iPod and MP3players are often used as examples of dematerialization because they are able to contain the same hours of music that was previously contained on many CD.	These electronic devices have been used for a too limited time (because of introduction of smartphones) to justify the substitution of previously used sustainable products. Their usage was too limited in time to be justified in terms of sustainability.

Table A9. Examples for clarifying the candidate causes of unsustainable beahavior when the product is over-used.

Candidate Causes of Unsustainable Behavior	Example	Reasons behind the Product Sustainability	Possible Reasons behind the Unsustainable Behavior
Overuse due to the perception of the low cost of the resources necessary for the operation of the EDP	A+++ TV sets	A+++ TV sets have a much lower energy consumption than their competitors and also have a furnishing function e.g., projecting pictures or simulating fireplaces.	They can be kept on for longer times than needed, as the user is aware of their limited energy consumption.
	LED lightbulbs	LED lightbulbs have a much lower energy consumption than incandescent bulbs.	They can be kept on for longer times than needed, as the user is aware of their limited energy consumption.
Overuse due to the high quality/price ratio of the EDP	Car sharing service	They are services providing a shared car fleet to the participants, who pay for the kilometers of travel, for the time of use or for a mix of the two. Therefore, the car owner has an economic interest in providing efficient and non-polluting cars.	The user benefits from this service instead of public transportation, also based on the advantages it provides, e.g., entering the town center.

Appendix D. Unsustainable Behaviors That Could Be Manifested during the End of Life Phase

Table A10. Examples for clarifying the candidate causes of unsustainable beahavior when the product is improperly disposed.

Candidate Causes of Unsustainable Behavior	Example	Reasons behind the Product Sustainability	Possible Reasons behind the Unsustainable Behavior
The product is difficult to be disassembled and materials cannot be easily separated	Electronic appliances	Although an electronic device may be designed to operate efficiently, if the end of life of these components is not managed properly the sustainable benefits gained during its use may be lost at the end of its life.	Since electronic devices consist of many different types of materials and often they are not designed to be disassembled by the user, the user might not follow the proper disposal way.
The user ignores or overlooks the correct way of disposing products	Specific materials, e.g., Tetrapak, bio-waste, zinc-carbon batteries	Waste management policies are very important for sustainability. However, the disposal policies are not same in every region/city.	There are different disposal regulations for every region/city. When people are not informed clearly, they might not act as desired due to the lack of knowledge or their habits.
	Multi-material packaging, e.g., Mila K3 Cap, food packages	By leveraging different materials, Mila has produced yogurt packaging with a much better overall environmental impact than plastic packaging. However, the materials have to be separated by the user at its end of life.	While reducing the plastic content of the packaging and substituting it with cardboard, potential advantages are turned into disadvantages if the user throws everything in the same recycle bin.

Table A11. Examples for clarifying the candidate causes of unsustainable beahavior when the product has become prematurely obsolete.

Candidate Causes of Unsustainable Behavior	Example	Reasons behind the Product Sustainability	Possible Reasons behind the Unsustainable Behavior
The product is perceived to be no longer competitive in terms of its technical performance	ICT products, e.g., PCs	The latest generations of ICTs are often more sustainable than their predecessors. However, to take full advantage of the sustainable benefits they have to be used for a minimum period of time.	Users might tend to substitute their PC prior to the end of its useful life, because they are attracted by rapidly increasing performances.
	Bio-degradable bags	Biodegradable bags are more sustainable than plastic ones and even these could be reused to make the most of their sustainable potential.	They are commonly disposed after a single usage although they could perform other functions.
The product is perceived to be no longer competitive because of changing (social) trends, fashion, consumers' preferences	Electronic devices, e.g., smartphones.	The latest generations of smartphones are often more sustainable than their predecessors. However, to take full advantage of the sustainable benefits they have to be used for a minimum period of time.	Smartphones have fashion aspect that exacerbate the willingness of their too early substitution.
	La sportiva shoes with replaceable sole.	La Sportiva offers a resoling service that allows the initial quality of the shoes to be regained.	The user might prefer to purchase another product instead of using the possibility of changing the sole of the owned shoes.

Table A12. Examples for clarifying the candidate causes of unsustainable beahavior when the product's life has been excessively extended.

Candidate Causes of Unsustainable Behavior	Example	Reasons behind the Product Sustainability	Possible Reasons behind the Unsustainable Behavior
The consumer is attached to the outdated product or would require (monetary) resources that they are not willing to sacrifice	Most sustainable cars (household appliances) at the time of buying.	Although a car (household appliance) from 20 years ago was designed following the eco-design guidelines of that time, it is not necessarily more sustainable than an eco-designed car of today. It would be wise to change it if the overall impact suggests so.	The users get attached to their car (household appliance) and they are reluctant to change it even it is no longer convenient also from an environmental perspective.

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