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# X-PEC – A Problem Expanding and Creativity Framework for Generating Effective Ideas to Improve Sustainability in the Early Stages of Product Development

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**Abstract:** This contribution highlights the significance of support methods for the early stages of sustainable product development and culminates in the introduction of a comprehensive framework in this domain. The framework aims at assisting designers and product engineers in generating and evaluating ideas for the development of product systems with high sustainability potential. The multi-iterative framework, whose effectiveness has already been demonstrated in diverse workshops, is tailored to support the early stages of the product development process. It leverages a fusion of creativity and evaluation techniques, identified through an extensive comparison of reputable techniques. Guided by predefined objectives, process steps, and additional inputs, the framework is structured to facilitate a systematic approach. Moreover, it incorporates an initial preparation phase aimed at consolidating essential information and clarifying the problem situation, the associated needs and further restrictions. Consequently, the framework consists of several techniques to comprehensively address the needs of sustainable product-system development.

*Keywords: Sustainability, Idea-Generation, Early-Design-Phase, Business-Models, Product-Development*

## 1 Introduction

### 1.1 Motivation

The irreversible damage resulting from the surpassing of planetary boundaries (Rockström et al., 2015) necessitates swift intervention and implementation in the way we satisfy our needs, as products and services can cause significant social, economic and environmental impacts and therefore play a decisive role in this context. However, for such a transformation to be reliably implemented, the measures must inherently possess considerable **sustainability potential**, rather than just optimizing existing concepts. Other critical factors are the **market potential**, as no product or service converts substantial sustainability potential if the market situation does not permit viable implementation as well as the **technical feasibility** of the approach. Consequently, these three aspects delineate essential characteristics for sustainable approaches aimed at curbing the surpassing of planetary boundaries and simultaneously ensuring the realization of the sustainable development goals by 2030 (UN, 2015). Early focus on these foundational aspects is crucial, as even highly refined development processes cannot rectify an ineffective idea later on. Recognizing the pivotal role of the initial stages of product development (PD), including the product planning and the concept phase, as outlined by Szeghö and Bercsey (2007), is essential for mitigating environmental impacts. This assertion is supported by the eco-design paradox (Chebaeva et al., 2021), which underscores the possible sustainability improvement in the early stages of the product development process (PDP). As innovative ideas are defined to encompass a technical or organizational novelty as well as a successful market adoption (Greunke, 2016), some of the identified critical factors are already addressed within the concept of innovation. To also achieve the necessary sustainability potential, a system-level innovation, as proposed by Cucuzzella (2016), is the preferred innovation variant. Function innovations, product redesigns, and subsequent improvements offer increasingly restricted options concerning the sustainability potential. While system innovations hold greater potential for sustainable improvement, their development necessitates a higher level of conceptualization, evaluation, and implementation (Cucuzzella, 2016), making their development an ambitious goal and demanding a structured and holistic PDP. Thereby, this contribution concentrates on establishing a foundation to translate the highest possible improvements in sustainability into practice, by proposing an eco-ideation framework designed to support the generation of sustainable and innovative product systems in the early stages of the PDP.

### 1.2 Aim of the research

On the basis of a literature research, conducted by the authors, the need and requirements for a holistic method to support the early stages of the PDP is to be emphasized. Additionally, the objective of this contribution is to examine and compare existing creativity techniques (CT) as well as evaluation techniques (ET), to elucidate their advantages and disadvantages. Building on these insights, a combination of the examined techniques is incorporated into a support framework, aiming to facilitate sustainable PD in the early stages. In this context, this contribution introduces X-PEC, a sequential, multi-phase, and versatile creativity framework with the goal of generating innovative ideas that contribute to sustainable development. By this means, the framework aims to support the development of solution principles that are technically feasible, possess high market as well as sustainability potential. Furthermore, these ideas are to be evaluated and refined through several iterations to ensure subsequent sustainability success to the best extent possible. Consequently, X-PEC can be perceived as a comprehensive ideation methodology that integrates various established CT and ET after determining the actual problem. Its primary objective is to bolster the ideation stage during the initial phases of the PDP. Therefore, it should not be viewed as a framework intended to span the entirety of the PDP. Rather, it serves as an iterative ideation process aimed at laying the groundwork for the subsequent stages of the PDP. In this work, solutions are assessed as sustainable across the whole product system according to the triple bottom line (TBL), i.e. if they are environmentally, socially and economically viable. However, it is essential to note that this work primarily addresses the ecological dimension. Additionally, the method aims to assist the user in understanding and, if necessary, expanding the considered problem.

## 2 Methods and methodologies in the early stages of Product Development

To optimally support the early conceptualization of a product, it is imperative that the fundamental ideas meet the requirements set forth by the respective stakeholders. This necessitates a concentrated focus on the origin of ideas. To ensure the efficient and valid generation and subsequent selection of these ideas, various techniques and frameworks have been developed in recent years, aiming to facilitate the early PDP and create optimal conditions for idea generation. These techniques contribute to idea generation in diverse ways. Some are designed to provide optimal framework conditions by clarifying the specific problem situation, as for example the progressive abstraction, as described by Geschka (1983), while others concentrate on offering optimal generating techniques, as for example the SCAMPER technique. Still, others emphasize the validation of already generated ideas and even focus on suitable combinations.

### 2.1 Challenges and chances in the early phases of product development

The eco-design paradox, as elucidated by Chebaeva et al. (2021) and grounded in the design paradox by Ullman (2003), constitutes a significant challenge in the early stages of the PDP. Concerning the standard design paradox, the necessary modification costs increase as the PDP advances, accompanied by a proportional reduction in design freedom due to accumulating design insights. Transposing this insight to the ecological potential of a product system, clarifies that the greatest sustainability potential lies in the early phases of PD (Chebaeva et al., 2021). Consequently, supporting and validating each early process step becomes imperative. However, since the foundational knowledge of developers is at its lowest at the origin of the PD, the validation of these ideas becomes more challenging. As delineated by Becerril et al. (2016), existing tools and methods for decision-making support are primarily tailored for later stages of PD, where changes to existing products are already constrained. Hence, the potential efficacy of support methods for the early stages is underscored. Building on this, previous work by Ferioli et al. (2008) affirmed the necessity for a decision-making tool capable of evaluating and classifying ideas during the early phases of the PDP. The importance of early-stage emphasis in the PDP is reinforced by the meta-review conducted by Willems et al. (2022), which concurrently recognizes substantial potential within the initial phases of the PDP. In pursuit of this objective, there is a recognized need for the development of additional capabilities grounded in the sustainability concept. Collectively, an emphasis on the early stages is deemed imperative in the field of PD. Indeed, an analysis of extant literature reveals a notable deficiency in current design methodologies for sustainable products, especially concerning the initial stages and the fostering of creativity in eco-innovation, as elucidated by Tyl et al. (2016) and Bocken et al. (2011). Furthermore, the oversight of the overall innovation promotion has constrained the presumed sustainability potential as posited by Cucuzzella (2016).

### 2.2 Requirements for the framework

To align with the aforementioned ambitious objectives and concurrently address the identified research gaps, the envisaged framework must adhere to specific criteria necessitating further clarification. Building upon the insights derived from the preceding research, the framework should possess adaptable applicability with a moderate level of complexity to ensure broad appeal. Furthermore, it ought to furnish a procedural approach capable of generating a diverse array of ideas, subject to successive qualitative refinement and reduction during each iteration step, as articulated by Sowrey (1990). The framework should possess the capability to integrate both the business model (BM) and the entire product life cycle, ensuring a comprehensive perspective. Given the dual imperatives of innovation and validity in the generated ideas, the framework must encompass suitable CT and ET, which must be determined systematically. In addition, it should offer pertinent inputs to facilitate its applicability. Moreover, the framework requires a robust connectivity to the subsequent PDP, recognizing its role in ideation rather than comprehensive PD. Considering these identified needs, the design mandates a multi-iterative and dynamic process, optimizing the efficacy of both CT and ET for specific problem situations. Finally the framework must support the user in determining the actual problem, prior to the ideation phase.

### 2.3 Creativity techniques: Fundamentals and comparison

The research of Chulvi et al. (2013) underscores that the usage of CT has a substantive positive influence on the idea density, novelty, and quality of ideas, highlighting the indispensability of such techniques in the early stages of the PDP. To therefore support effective idea generation and contribute to early-stage PD, a multitude of CT has been developed in recent years. According to Smith (1998), there were already over 170 successful CT by 1998, showcasing the diversity of this field. Shah et al. (2000) classifies CT as intuitive, discursive and intuitive-discursive. According to this classification, intuitive techniques are generally suitable for generating a large quantity of ideas in a short amount of time but may exhibit a suboptimal degree of quality. Discursive techniques, guided by strategic framework instructions, tend to generate a lower quantity of ideas, yet with noticeably higher quality. In the case of combined CT, evaluating the quality or quantity of generated ideas is challenging, as it depends on the respective share. For instance, the Walt-Disney-Method, described by Schawel and Billing (2009), is an intuitive-discursive CT with a significant intuitive share, designed to generate a relatively large number of ideas in a short time (Dilts, 1994). In contrast, TRIZ, also classified as an intuitive-discursive technique by Vargas et al. (2012), may generate a substantially lower number of ideas, which however tend to be more novel (Chulvi et al., 2013), due to the predominant discursive share (Vargas et al., 2012). Rather than relying on a single CT, a subordinated creativity framework, with specifically determined techniques, appears more practical, offering greater flexibility and efficacy. To systematically identify the most suitable CT, the authors conducted a comparative analysis with 41 CT. This comparison serves as the foundation for distilling the crucial aspects of these techniques and is essential for the development of an effective support technique for the early stages of PD. Additionally, the potential synergies between different CT are explored to validate the thesis that none of the compared techniques can meet all needs independently. In this comparative analysis, CT are categorized according to the classification of Shah et al. (2000), distinguishing between intuitive (I), discursive (D), and combined (C) techniques. The comparison considers the following aspects: number of participants, complexity, time expenditure, quantity of ideas, quality of ideas, expandability, reliability, controllability, innovation support and influencing of the team, while the bold marked techniques represent sustainable-oriented CT. For the number of participants, 'N' signifies an arbitrary number of participants. Notably, complexity, quantity of ideas, and time expenditure are the most meticulously analyzed criteria in developing the creativity framework, since the assumption of Sowrey (1990) demands an initially high output of ideas, which will be reduced gradually. An excerpt of this comparison, utilizing a scale limited to five intensities ranging from very low to very high, is presented in Table 1.

Table 1. Comparison of creativity techniques

| Symbol Rating: ● Very high, ◕ High, ◑ Moderate, ◔ Low, ○ Very Low | | Assessment Aspect | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Classification | Participants | Complexity | Time expenditure | Quantity of ideas | Quality of ideas | Expandability | Reliability | Controllability | Innovation support | Influencing of team |
| Creativity-techniques | Brainwriting/Brainstorming | I | N | ◔ | ○ | ● | ◔ | ● | ◔ | ◔ | ◔ | ○/● |
| | (**Sustainable**) Mindmap | I | N | ◔ | ○ | ● | ◔ | ● | ◔ | ◑ | ◔ | ● |
| | Chat GPT-4 | I | N | ○ | ○ | ● | ◔ | ◔ | ◔ | ◔ | ◑ | ○ |
| | Progressive Abstraction | D | N | ◕ | ◑ | ◑ | ◑ | ◕ | ◔ | ◑ | ● | ◔ |
| | SCAMPER | D | N | ◑ | ◑ | ◑ | ◕ | ◑ | ◕ | ◕ | ◑ | ◔ |
| | **Eco-ideation tool** | D | N | ◑ | ◑ | ◑ | ◑ | ◕ | ◑ | ◑ | ◑ | ◔ |
| | **ESM-toolbox** | C | N | ◑ | ● | ◑ | ◕ | ◔ | ◕ | ◑ | ● | ◔ |
| | Walt-Disney-Method | C | ≥3 | ◔ | ◔ | ● | ◔ | ◕ | ◑ | ◑ | ◑ | ◕ |
| | **7 thinking hats** | C | 7 | ◑ | ◑ | ◕ | ◑ | ◑ | ◑ | ◔ | ◕ | ● |
| | **TRIZ** | C | N | ● | ● | ◑ | ◕ | ◔ | ◕ | ◑ | ◕ | ◑ |
| | … | | | | | | | | | | | |

The table above reveals that the complexity of purely intuitive CT is typically considerably lower compared to discursive and combined approaches. Only combined CT with a substantial intuitive component deviate from this pattern. Furthermore, most CT seem manageable in terms of the time required for their execution. In terms of the number of ideas generated, intuitive CT that do not require a long lead time are the most convincing and can generate a large number of ideas within a very short duration. (Garfield et al., 2001) Particularly surprising are the outcomes pertaining to Chat-GPT, which demonstrates a remarkably efficient idea generation process within an exceedingly brief timeframe. On top of that, its impact on other participants is negligible, and its overall complexity is significantly low. This technique could serve as a representative example for other artificial intelligence tools, thereby highlighting their considerable potential in idea generation processes. However, when considering the reliability and quality of ideas, as well as the maturity of the generated approaches, intuitive CT lag significantly behind discursive approaches. Consequently, it is crucial to conduct a particularly precise, possibly multi-stage, evaluation of the ideas when employing purely intuitive CT. Based on this, the use of techniques with a high discursive share, due to their flexibility, appears promising in the early stages of the PDP. As the comparison demonstrates, no single CT excels in all categories. Therefore, the hypothesis has been substantiated, emphasizing the need for the development of a superimposed framework from individual CT. In addition to established CT such as brainstorming or SCAMPER, innovative approaches like the ESM toolbox by Tyl et al. (2016) or the eco-ideation tool by Bocken et al. (2011) have been incorporated in this comparison. However being developed to facilitate the generation of sustainable ideas, these methods often only focus on addressing specific environmental aspects rather than aiming for holistic sustainability. Moreover, it is notable that many sustainable CT just represent incremental adjustments to existing techniques. For instance, Dekoninck et al. (2007) proposed simplified tools based on TRIZ for eco-innovation, while König et al. (2023) modified the “Six Thinking Hats”-method by incorporating an additional perspective to enhance its lightweight and sustainability characteristics. Thereby, the integration of sustainability components into most CT seems conceivable through minor adjustments, as illustrated by König et al. (2023) and Dekoninck et al. (2007). However, their efficacy warrants meticulous evaluation since these methods are often only applicable in specific scenarios. On top of that, these methods also highlight the need for overarching methodologies that can leverage a multitude of such techniques. In response to this need, more ambitious approaches have emerged, such as the UNEP eco-innovation manual, illustrated by O'Hare et al. (2014), and the systematic lightweight creativity methodology by König et al. (2023), integrating lightweight and sustainable design in the ideation stage. These methodologies aim to fulfill the required needs in a more comprehensive and effective manner by providing a procedural model that integrate diverse sustainability-oriented CT and guide users through the ideation process.

### 2.4 Evaluation techniques: Fundamentals and comparison

After generating ideas, the next systematic step, as required by the framework specifications, is their evaluation before proceeding to further development in the PDP. The evaluation of ideas can be conducted with varying intensities over different iterations. The choice of the ET depends, besides other aspects, on the specific objectives, the maturity and on the quantity of ideas. Some techniques are effective when applied to a small number of ideas, while others are suitable for a larger dataset. For instance, the SWOT-analysis, as described by Schawel and Billing (2009), is an example of a technique limited in quantity and may not be effective for evaluating a multitude of ideas. It is noteworthy that ideas can be evaluated qualitatively, quantitatively, or through a combined approach. Given that many ideas lack accountable datasets, quantitative analysis may be challenging, making qualitative analysis more suitable, particularly in the early stages of PD. To pinpoint the most suitable ET and ascertain their optimal application areas for the framework, the authors identified and compared 21 techniques, drawing from the research conducted by Schawel and Billing (2009), along with techniques selected by the authors. The criteria used for analyzing these techniques include complexity, intuitiveness, time expenditure, quantity of ideas, uncertainty, and the degree of freedom. ET in this comparison are categorized as qualitative (Ql.), quantitative (Qt.), and qualitative-quantitative (QQ) ET. As mentioned earlier, the number of efficiently manageable ideas and time expenditure are considered the most important aspects in this comparison.

Table 2. Comparison of evaluation techniques

| Symbol Rating<br>● Very high<br>◕ High<br>◑ Moderate<br>◔ Low<br>○ Very Low | | Assessment aspects | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Classification | Complexity | Intuitiveness | Time expenditure | Quantity of ideas | Uncertainty | Degree of freedom |
| Evaluation techniques | Kano-Diagram | Ql. | ◔ | ◕ | ◔ | ● | ◑ | ◑ |
| | Decision matrix (unweighted.) | Ql. | ◑ | ◑ | ◔ | ◑ | ◕ | ◕ |
| | SWOT | Ql. | ◔ | ◕ | ◕ | ◑ | ◑ | ◕ |
| | HOWNOWWOW-Matrix | Ql. | ◔ | ◕ | ◑ | ● | ◕ | ◑ |
| | BMC | Ql. | ◑ | ◑ | ◕ | ◑ | ◑ | ◑ |
| | Triple-Layered-BMC | Ql. | ◕ | ◑ | ● | ◔ | ◕ | ◑ |
| | Fast-Five Checklist | Ql. | ◔ | ◑ | ◔ | ◕ | ◑ | ◔ |
| | Ten Golden Rules | Ql. | ◑ | ◑ | ◑ | ◑ | ◑ | ◔ |
| | LCA | Qt. | ● | ◔ | ● | ◔ | ◔ | ◔ |
| | MCDM | QQ. | ● | ○ | ◑ | ◔ | ◑ | ● |
| | ... | | | | | | | |

Based on the table above, it is advisable to avoid using a standalone ET since none of the techniques can fulfill the requirements in every segment. This confirms that, similar to CT, utilization of multiple ET seems to be the best choice at fulfilling the requirements of the framework. When considering the aspect of uncertainty, it is noticeable that techniques with low complexity often come with an increased uncertainty factor, which results from their partly superficial nature. Regarding complexity, it can also be determined that quantitative techniques and qualitative-quantitative techniques exhibit a higher degree of complexity than purely qualitative ET. A similar observation must be made for the required time, which is usually higher in more complex ET. Moreover, the comparison reveals that many of the ET, while not universally applicable, exhibit a high degree of freedom and demonstrate good efficacy. In light of these observations, a dynamic validation of ideas emerges as the most suitable approach to fulfill the framework requirements.

In view of the presented examinations, it is imperative to address the identified deficits, such as the absence of sustainability potential, innovation, and more, through the implementation of a holistic framework, being able to utilize the multitude of already existing CT and ET.

## 3 The X-PEC Framework

In this paragraph, the functionality of the Problem Expanding and Creativity (X-PEC) framework will be highlighted in detail. The name is composed of the presented acronym and also refers to the verb "to expect something", which is due to the fact that the sustainability effect shall already be estimated through early evaluation iterations. The letter "X" represents a placeholder for various problem situations in diverse industries that can be managed with the framework. The fundamental procedure of the framework aligns with the structure outlined in VDI 2221 (2019). It adopts a dynamic and iterative approach involving alternating activities following a thorough preparation phase, as illustrated in Figure 1. In this context, a creativity activity is followed by an evaluation activity so that the generated ideas can be controlled systematically. This procedure is initiated with a given input, which is composed of the adapted problem situation and the target, adapted for the first phase. Throughout the whole process, the generated ideas are collected in the temporary storage as interim results. Besides the preparation phase, the framework is thus composed of three main domains: Activities, interim results as new output, and additional input. The entire sequence thus resembles a control circuit where the activities represent the control device (CT) and the measuring element (ET) that needs to be adjusted to achieve the desired goals, ensuring effective controllability within this ideation framework. This critical aspect is particularly overlooked in comparable contexts. In this sense, the initially high number of generated ideas will be decreased after each evaluation activity so that the set is reduced to a manageable size for the following iterations, while the maturity of ideas increases significantly, following the approach of Sowrey (1990).

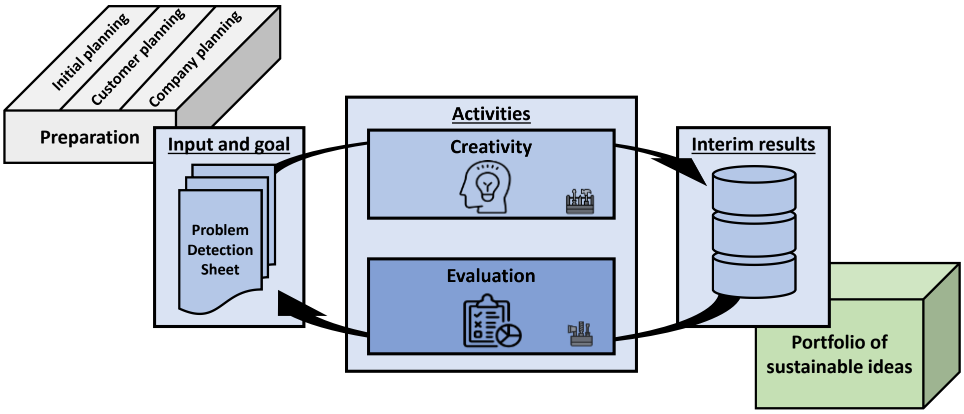


Figure 1: Overview of the X-PEC framework based on VDI 2221

Each activity contains a toolbox featuring a multitude of flexibly applicable CT or ET, which serve as additional resource on top of the main creativity iteration. The provided toolbox consist of the numerous CT and ET options analyzed in the above comparison. At the end of the framework, the accumulation of information for a portfolio of sustainable ideas (PSI) is contemplated. This means that the framework not only intends to generate pre-evaluated ideas but also places importance on gathering information. The PSI includes various information, such as the results of a SWOT analysis, rejected ideas, or hypothetical BMs that could be implemented in the future. The ultimate goal of the PSI, and therefore the framework, is to support designers in realizing the final product by providing a multitude of design choices. This implies that a comprehensive PDP must be conducted subsequently to bring a valid product system to fruition. Consequently, the framework doesn't limit itself to generating only one idea, as the validity of a single idea could pose difficulties in the subsequent PDP.

### 3.1 Preparation phase of the X-PEC framework

The preparation phase encompasses diverse analysis and synthesis techniques specifically devised to accumulate relevant information for subsequent creativity iterations. The analytical methods are instrumental in scrutinizing the prevailing enterprise situation, whereas the synthesis methods are oriented towards establishing target criteria and elaborating upon the initial problem. Its main objective is to establish an initial understanding of the current situation and identify general conditions conducive to generating ideas that align with the target criteria identified in this phase. Customized for different use-cases, the preparation phase addresses three primary scenarios: initial planning, customer planning, and company planning. Each use-case comes with its own set of considerations regarding sustainability potential and implementation risk. The initial planning scenario presents the largest potential for sustainability, but also poses the highest level of uncertainty, due to its vast creativity horizon. On the contrary, the customer and company planning scenarios offer higher safety levels as many conditions are predefined, although resulting in a reduced creativity potential. Each use-case has a distinct entry point into the framework, and the input is adjusted accordingly. For example, the company planning scenario requires no additional input and can seamlessly follow the preparation schedule, as visualized in Figure 2.

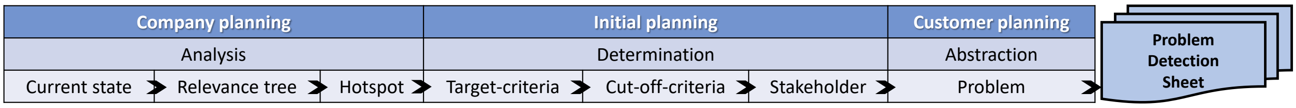


Figure 2 Overview of the preparation phase

For the initial planning scenario, certain analyses such as the current enterprise situation, hotspot analysis, and relevance tree analysis are skipped before following the same process as the company planning, as there are no existing business structures to restrict the planning. However, it involves providing input for a comprehensive market and patent analysis to establish a robust market situation. Since most of the restrictions, policies, and targets originate directly from the customer, the customer planning focuses solely on abstracting the initial problem context, with the progressive abstraction technique. For example, the task of designing a sustainable toothbrush can be expanded to encompass the design of sustainable teeth cleaning approaches, extending beyond the singular focus on the toothbrush. This adjustment results in a more fitting and comprehensive problem situation. This abstraction process can help clarify the actual problem without unnecessarily limiting the creative scope. This step in the framework is crucial as the initial idea generation is primarily derived from the problem situation, making it a fundamental aspect considered in all three use-cases. The information gathered in the preparation phase is compiled on the Problem Detection Sheet (PDS), a physical template that includes categories such as widened problem, context description, investigation framework, target criteria, stakeholders, company resources, policies, current BM, in-scope aspects, and out-of-scope aspects. The PDS serves not only as a record of these essential aspects but also as a tool for further adapting the problem. The initially widened problem is therefore modified with the help of the identified restrictions to enhance the feasibility of ideas, creating an optimal input for idea generation for the framework.

### 3.2 Main phase of the X-PEC framework

To meet the challenging requirements, such as the technical feasibility and the high sustainability potential, and at the same time provide the highest degree of flexibility, an intuitive-discursive overall approach is chosen for X-PEC. This methodological choice harmonizes the simplicity inherent in intuitive techniques with the precision afforded by discursive components, thereby presenting a balanced and efficacious procedure within the X-PEC framework. To increase this flexibility even further, X-PEC offers a continuous input feature, serving as cross-iteration support for both idea generation and evaluation. This continuous input is intentionally designed to furnish users with sustainability insights, delivering valuable information throughout the idea generation process without imposing rigid directives. The content of this cross-iteration input includes an impact evaluation table that lists various impacts within the TBL, the Ten Golden Rules by Luttrop et al. (2006), and the design pilot toolbox, developed by Schabbach (2023). On top of that, the continuous input for ET consists of the triple-layered-business model canvas developed by Joyce and Paquin (2016), and common examples of product-service-systems (PSS), as delineated by Tukker (2004). The structural framework of X-PEC unfolds across seven primary iterations, each endowed with a specific goal. These objectives are strategically devised to systematically diminish the initially abundant pool of generated ideas in successive steps, concurrently elevating their quality and maturity. Following the initial design of the framework, it underwent practical application in numerous creativity workshops with the dual objectives of identifying weaknesses and validating its functionality. These workshops, held in collaboration with partner companies and attended by participants with backgrounds in sustainable PD, focused on the design challenge of creating a sustainable toothbrush, an accessible yet diverse topic, chosen to assess the framework's efficacy. The problem was extended to the sustainable cleaning of teeth, which initiated the start of the idea generation. The workshops yielded a diverse array of interesting ideas, providing valuable insights that informed subsequent adjustments to the framework. Importantly, they demonstrated that X-PEC is quite effective in both generating and evaluating sustainable ideas. Notably, an additional evaluation phase, absent in the initial version, was incorporated to provide participants with an early comprehension of the generated ideas. This addition was crucial as initial misconceptions had previously hindered the efficacy of the procedure. Another pivotal adjustment involved the customization of the toolboxes, initially less comprehensive, allowing participants greater flexibility, rather than being confined to the presented options. In this context, sustainability-oriented CT, such as a sustainability-focused Mindmap, were incorporated. The most recent iteration of the framework is depicted in Figure 3. However, it is essential to note, that the procedure and the suggested CT and ET are not strictly sequential and the model in Figure 3 just serves as an illustrative example rather than a rigid sequence.

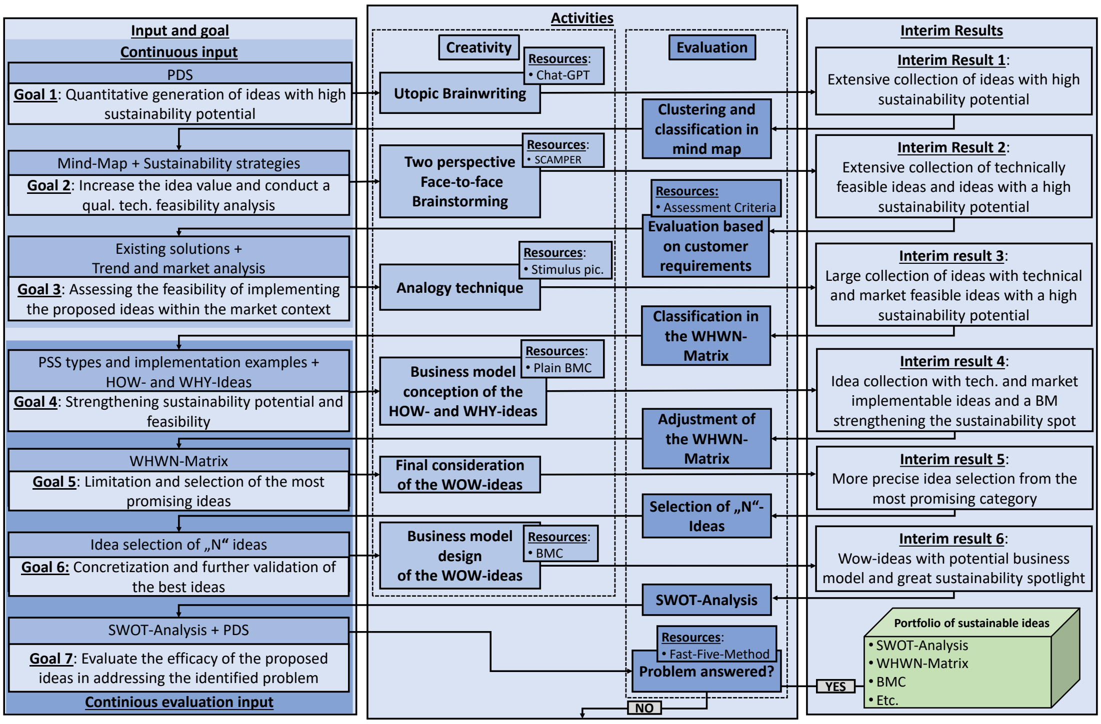


Figure 3: Detailed presentation of the main phase of the X-PEC framework

Goal 1: Quantitative generation of ideas with high sustainability potential

In accordance with the observations highlighted by Sowrey (2019), the initial phase of the X-PEC framework is designed to generate a substantial number of ideas during the early stages of the creativity process, a critical prerequisite for effective creativity processes. To achieve this objective, CT, characterized by a high output number of ideas, identified in table 1, are strategically employed. Simultaneously, a requisite input, besides the PDS, is instituted to ensure that the generated ideas possess the utmost potential for sustainability. Given its demonstrated efficacy in facilitating a prolific idea generation with minimal participant influence, the brainwriting technique is selected as the primary CT for this phase. To enhance the sustainability potential of this step, a utopic brainwriting approach, similar to the Walt Disney method, is implemented. Additionally, to augment the accumulation of ideas, optional CT identified for their high idea output, as delineated in the comparative analysis, such as Chat-GPT and the ABC-method, can be employed. Following the generation of a multitude of ideas, the subsequent evaluation task involves clustering and classifying these ideas in a mind map. Granting an overarching understanding of all generated ideas, the mind map establishes a foundational comprehension, essential for the consolidation and further development of these ideas.

Goal 2: Increase the idea value and conduct a qualitative technical feasibility analysis

With the overarching objective of generating viable ideas possessing a high degree of sustainability potential, emphasis is placed on ensuring the technical feasibility of the ideas. This is achieved through a face-to-face brainstorming session, where participants are specifically instructed to generate ideas that are both feasible and sustainable, while categorizing their ideas within the three sustainability strategies: efficiency, sufficiency, and consistency, as described by Haase (2020). This classification serves as a cognitive trigger for participants to align their thinking with these strategies, thereby fortifying the overall sustainability character of the generated ideas and further organize the PSI. Importantly, previously generated ideas are incorporated into this step. Given that this iteration focuses on further organizing and evaluating the technical feasibility of the existing ideas, the idea output during this iteration is relatively low. The output is primarily supplemented with ideas stimulated through cognitive stimulation subsequent to the presentation of all ideas in the preceding phase and through the categorizing in the sustainable strategies. To streamline the pool of ideas following this step, an exclusion process is implemented, guided by predetermined assessment criteria rooted in the identified stakeholder requirements. This exclusion process is mainly done in a qualitative way but can be expanded with specified weightings depending on the use-case and density of ideas, for example with a multi-criteria decision analysis.

Goal 3: Assessing the feasibility of implementing the proposed ideas within the market context

Up to this point, the ideas have been generated solely through a static approach without external assistance. The third iteration is designed to advance the ideas using the analogy technique, involving a comparison of the generated ideas with stimulus pictures and already established solutions for analogous problems. This process aims to enhance the ideas, elevating their overall quality. Additionally, comparing them to existing products contributes to validating their feasibility in the market, a crucial criterion for sustainable innovation, according to Greunke (2016). To further assess the feasibility of the ideas, a categorization matrix, based on the Hownowwow-matrix, as delineated by Przybylek and Kowalski (2018), is employed. The matrix, ensuring considerations of market potential, technical feasibility, and sustainability potential, includes the following categories: No, why, how, and wow. Ideas relegated to the No-Category lack convincing attributes in all criteria and are excluded from further iterations. The Why-category encompasses ideas that are technically feasible but fall short in demonstrating sufficient sustainability potential. Given the paramount importance of technical feasibility, ideas failing to convince in this regard are placed in the How-category. The Wow-category comprises ideas that successfully fulfill all criteria. Accordingly, the ultimate objective of the framework is to identify ideas that can be evaluated or further developed as Wow-ideas. With the categories of the WHWN-matrix established, the subsequent step involves categorizing the already developed ideas within this matrix, excluding those in the No-category.

Goal 4: Strengthening sustainability potential and feasibility

Given that the BM has not been integrated into the idea generation process thus far, this iteration is dedicated to incorporating the BM for the Why- and How-ideas. The objective is to enhance the missing sustainability potential or technical feasibility of these ideas through the strategic integration of a BM. This incorporation is carried out qualitatively and can be facilitated by employing a straightforward BM canvas template, as described by Osterwalder et al. (2005), or common PSS-types, as delineated by Tukker (2004). The observations made by Blüher et al. (2020) have indicated that the implementation of PSS can yield significant sustainability benefits, with a particular emphasis on mitigating natural resource use and preventing pollution, especially in the context of addressing mobility services, such as car-sharing. Only ideas that successfully acquire sustainability potential, in the case of why-ideas, or achieve technical feasibility through the integration of the BM, in the case of how-ideas, advance to the Wow-category, which serves as the ultimate target category. This selective progression ensures that ideas reaching the Wow-category possess a well-aligned and viable BM, contributing to their overall feasibility and sustainability. This step primarily centers on the creative activity, with the evaluation activity limited to the adjustment of the WHWN-matrix.

Goal 5: Limitation and selection of the most promising ideas

In this methodological step, the objective is to further refine and conduct a final assessment of the Wow-ideas before identifying the most promising solutions within this category. In terms of creative effort, this step is minimized, as the primary focus shifts to the subsequent validation activity. Nonetheless, a conclusive consideration of these ideas is imperative. Once the ideas have undergone finalization, the most promising Wow-ideas are selected. To facilitate the use of techniques generating well-secured ideas, the density of ideas for more intricate ET needs to be reduced, necessitating a notably high number of excluded ideas. This selection process can be executed through any suitable scheme, however preferably employing a comprehensive utility value analysis with carefully weighted evaluation criteria, as described by Dittmer (1995). The number of ideas to be selected is contingent on the time constraints of the participants in subsequent phases but should comprise at least two ideas.

Goal 6: Concretization and further validation of the best ideas

Upon the identification of the most promising ideas, a detailed refinement of these concepts in relation to their corresponding BMs ensues. Given the pivotal role that the BM plays in influencing the level of innovation (Rantala et al., 2018) and, consequently, the potential for sustainability (Cucuzzella, 2016), including adherence to the principles of the circular economy (Bocken et al., 2016), a meticulous analysis of the constituent elements within the BM structure becomes imperative. To facilitate users in this pursuit, exemplars of business model canvases and patterns, such as those elucidated by Lüdeke-Freund et al. (2022), Joyce and Paquin (2016) and Osterwalder et al. (2015), are proffered. The primary aim is to serve as a source of inspiration and guidance for individuals engaged in this endeavor. Given that X-PEC aspires to accumulate a PSI, it is noteworthy that these ideas don't need to be singularly allocated to a specific BM. The primary objective here is to acquire viable BMs, which will undergo a more detailed selection during the subsequent PDP. Following comprehensive discussions on the potential BMs, the identified ideas undergo a SWOT analysis, as delineated by Schawel and Billing (2009). This analytical process serves the dual purpose of further validating the functional viability of the ideas and enriching the PSI.

Goal 7: Evaluate the efficacy of the proposed ideas in addressing the identified problem

The ultimate phase of the framework dispenses any further creative activities, as the ideas have already undergone comprehensive development through multiple iterations. Central to this phase is the imperative question of whether the generated and refined ideas align with the criteria delineated by the respective stakeholders. Given the inherent complexity of this inquiry, users are aided in their assessment by employing a set of five comparative questions spanning various domains. The ideas are systematically evaluated against benchmarks, as similar or previous product systems. Subsequently, it is to determine whether the new concept exhibits superior performance technologically as well as across the TBL. Should an affirmative response be elicited, the PSI is deemed complete, opening the way for the subsequent PDP. Conversely, if the response leans towards the negative, necessitating a renewed iteration. This entails an adapted problem definition, along with a re-specification of target criteria and constraints.

## 4 Discussion

Although the framework and its techniques have already demonstrated its efficacy in multiple workshops, it is imperative to continue its development, as the ultimate objective is for enterprises to autonomously utilize the framework. Therefore, it is essential to subject the framework to further testing, with participants employing it autonomously, devoid of direct researcher assistance. This approach is crucial for fostering self-sufficiency among users. Additionally, comprehensive validation efforts involving diverse problem situations, indispensable to discern the framework's applicability and delineate exclusion scenarios. Moreover, the framework requires rigorous testing to ascertain its comprehensiveness, involving comparisons with prevailing industry standards and analogous frameworks. Another notable limitation lies in the predominantly qualitative nature of the ET, necessitated by challenges in acquiring justified datasets. On top of that, enhancements in the preparation phase are warranted, incorporating a more extensive array of use-case scenarios to accommodate a broader spectrum of enterprise situations. Beyond that, a critical examination of the chronological sequencing of the framework steps is imperative, particularly in light of the significant impact that the inclusion of BMs may exert when introduced at an earlier stage. Similar scrutiny is applicable to the provided techniques, as their deployment also holds a decisive role in shaping the overall process. Lastly it should be addressed that the static structure of X-PEC presents a notable limitation attributed to its pioneering yet inflexible modules. Consequently, for a forthcoming iteration of X-PEC, the desirability of incorporating dynamic adjustments through a computer-aided tool is emphasized.

## 5. Conclusion

This contribution underscores the significance of a comprehensive methodology designed for sustainable idea generation and evaluation in the early stages of the PDP. It strives to offer product engineers and designers a possibility to harness the sustainability potential of their products by focusing on the early sustainability ideation and the actual problem. The approach provides the user with resources to systematically analyze the problem in order to find the most fitting ideas with a high sustainability potential. The presented multiphase model, which stepwise development has been shown by analyzing and comparing several CT and ET, comprises stages such as problem expanding, idea generation and evaluation, based on the VDI 2221 (2019). Furthermore, the contribution emphasizes that the development of innovative and sustainable products necessitates an early awareness, a holistic consideration of the life cycle and strategic planning. In response to the challenges inherent in navigating the framework, a toolbox comprising stage-specific CT and ET was introduced. The stage-specific techniques devised for this purpose span a spectrum, encompassing well-established approaches as well as novel techniques, adapted for sustainable purposes. The proposed techniques can be utilized individually, based on personal preferences of the respective user, guaranteeing a high degree of flexibility based on specific use-cases, while also complying to the approach of Sowrey (1990). Additionally, in order to validate the functionality of the framework, it has been tested in various fictional creativity workshops with partner companies, proving that X-PEC supports the generation of sustainable ideas. However, further work will include more testing in real company environments, to validate the degree of effectiveness. Nonetheless, the validation of X-PEC remains critical. A rigorous validation process entails the same team performing the same task once with the utilization of X-PEC and once without it. Subsequently, both outcomes must be analyzed in terms of sustainability criteria to ascertain the effectiveness and impact of X-PEC.

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