INTERNATIONAL DESIGN CONFERENCE – DESIGN 2024
https://doi.org/10.1017/pds.2024.142

What's the catch? Trade-off challenges in early design for sustainability

Giácomo Parolin ✉, Tim C. McAloone and Daniela C. A. Pigosso
Technical University of Denmark, DTU Construct, Denmark
✉ gipar@dtu.dk

Abstract
Trade-offs involving multiple criteria that cannot be satisfied at the same time are ubiquitous in engineering design activities. Navigating trade-off decisions can be challenging, especially when it comes to sustainability-related decisions in early-stage projects. Through a systematic literature review, we unravel the challenges related to sustainability trade-offs in technology development, concept design, and other front-end of innovation activities. The challenges, which were evaluated by experts from industry and academia, range from technical and organisational to psychological aspects.

Keywords: decision making, technology development, ecodesign, systematic literature review, trade-off

1. Introduction

Manufacturing companies looking to integrate sustainability into their early-stage design and innovation processes often must make tough decisions that place sustainability aspects in conflict with business imperatives (Byggeth and Hochschorner, 2006; Farrukh and Holgado, 2020). When there are no solutions that can satisfy multiple objectives at once, a trade-off situation occurs (Andreasen et al., 2015). In a trade-off, one must make compromises between design properties (e.g., cost must increase to reduce a product's carbon footprint) (Luttropp and Lagerstedt, 2006). Trade-offs are integral activities in engineering design, which is a process that can be described as a series of decisions and compromises (Hazelrigg, 1998; Renzi et al., 2017) often under complexity and uncertainty, that involves multiple objectives and multiple stakeholders with conflicting interests (Kravchenko *et al.*, 2020a).
Trade-offs are specially challenging in the context of **early design for sustainability** in manufacturing companies (Pigosso et al., 2014). **Early design** includes technology development, conceptual design, architecture development, portfolio management, and other front-end of innovation activities (Koen et al., 2001). Dealing with trade-offs in these very uncertain and dynamic early design activities brings forth additional challenges to an already demanding task (Parolin et al., 2023a). Furthermore, decisions related to **sustainability** add an extra layer of challenges when navigating trade-offs (Luttropp and Lagerstedt, 2006). Sustainability can be a broad, somewhat intangible, and value-ridden concept, which makes defining and assessing it a difficult undertaking (Sala et al., 2015; Stevels, 2001).
While there are several tools and approaches to support trade-off decisions (including Multiple Criteria Decision Methods (MCDM), such as Multi-Attribute Utility Theory (MAUT) and Analytic Hierarchical Process (AHP) (Belton and Stewart, 2002)), manufacturing companies still struggle to effectively employ them (Parolin et al., 2024). Other scientific disciplines, such as Decision-Based Design (Hazelrigg, 1998) and Systems Engineering (Parnell et al., 2010), also propose several tools to deal with engineering design decision making. However, most normative decision-making methods (such as

MCDM) start from assumptions of clear decision contexts and alternatives, rational actors, almost complete certainty, and the possibility of mathematically modelling the preferences of decision makers (Belton and Stewart, 2002). These are often not the case in the fuzzy early-stage design activities focused on sustainability (Parolin et al., 2023a). Furthermore, existing tools might be hard to use or not well tailored for the research and development process (Villamil and Hallstedt, 2021).

Consequently, there is a need for effectively supporting trade-offs in early design for sustainability (Parolin et al., 2024). Having this as our fundamental goal, this paper aims to investigate **the challenges that manufacturing companies face when dealing with trade-offs in the context of early design for sustainability**. What are barriers and potential solutions for successfully integrating sustainability into decision making at the front end of innovation? We explore this topic via a systematic literature review and synthesis (Denyer et al., 2008) of trade-off challenges in engineering design, resulting in a set of 23 challenges. This research contributes to the existing body of literature by 1) synthesizing challenges related to trade-offs, 2) evaluating the challenges from the point of view of subject matter experts in a series of interviews and workshops, 3) indicating future research avenues for decision-making in early design for sustainability.

2. Background: key concepts in trade-off management

Trade-offs can be described as decisions when a compromise is made in one **property** of a design to obtain benefits in another (Figure 1). The **properties** of a design object describe its behaviour (e.g., stiffness, recyclability, quality) while **characteristics** relate to physical aspects like geometry and material (e.g., dimensions, colour) (Weber and Deubel, 2003). Trade-offs could also be described as conflicts in relation to characteristics, but in any case, they are originally caused by conflicts in properties. Additionally, properties can be placed in a spectrum from more objective (e.g., weight) to more subjective or more dependent on contextual factors (e.g., quality, aesthetics, sustainability).

Other concepts closely related to those of properties and characteristics in engineering design and decision making are **requirements**, **criteria**, **goals, virtues**, and **indicators**, also shown in Figure 1. Engineering design process models often prescribe the definition of **requirements** at the start of product development (Bertoni et al., 2018). Even though requirements are mostly related to properties (Weber and Deubel, 2003), they can also be deployed to refer to characteristics of the product. Criteria are the basis for any engineering decision making process, and can also be referred to as objectives, goals, values, or point of views (Belton and Stewart, 2002). In this article, we differentiate **criteria** to correspond solely to properties closer to the objective end of the spectrum, while **goals** refer to more subjective or contextually-dependant properties. Furthermore, properties can sometimes be called universal **virtues**, due to their importance in a product's life cycle (Olesen, 1992). Finally, **indicators** are measurable translations of properties or characteristics, and can be split into lagging indicators when closely related to properties and leading indicators when linked to characteristics (Parolin et al., 2024).

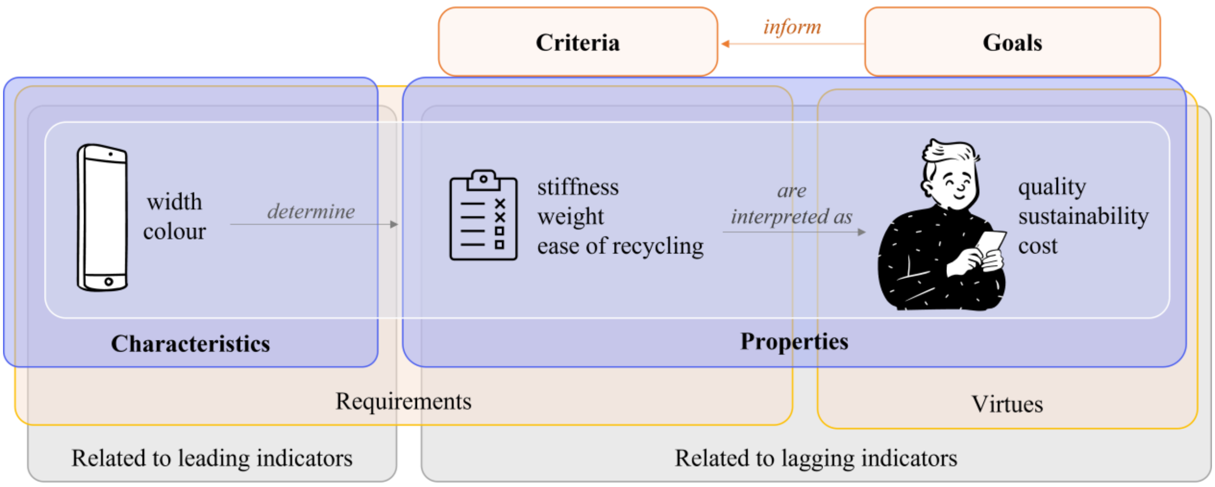

Figure 1. Characteristics, properties, and how they relate to decision criteria and goals

Trade-offs related to sustainability can be categorised according to which properties are in conflict. **Inter-property trade-offs** conflict sustainability related aspects with other properties of the design. A stereotypical inter-property compromise is one that puts an improvement in a sustainability property (e.g., reduction in particulate matter emission) against traditional business imperatives (e.g., manufacturing cost) (Luttropp and Lagerstedt, 2006). On the other hand, **intra-property trade-offs** put two sustainability-related aspect against each other - this is usually what is referred to as a sustainability trade-off in extant literature (Byggeth and Hochschorner, 2006). An example would be an electronic device with a reduction in use-phase energy consumption at the expense of increasing critical raw material consumption for manufacturing. Intra-property trade-offs are sometimes called "offsets" (Morrison-Saunders and Pope, 2013), "problem shifting" or "burden shifting" (McAloone and Pigosso, 2018). They can happen between life cycle phases (e.g., more water consumption during manufacturing at the expense of water consumption during use-phase) or between types of environmental impacts (e.g., lower biodiversity impacts but sacrificing recyclability).

3. Research methodology

This study employed a mix of systematic literature review and empirical work to extract (Denyer et al., 2008) synthesise and evaluate a list of challenges related to trade-offs in early design for sustainability. The search was conducted in the Scopus database, which is recognized and widely used in the engineering design community. The keywords were related to "trade-off", "challenge", and "early-stage design", including synonyms, within engineering design and the built environment. Results were screened according to PRISMA guidelines (Page et al., 2021). Out of 500 search results, 42 papers were included in the final sample. Complete literature review data (including search strategy, inclusion, and exclusion criteria, flowchart, data extraction, and data analysis) is available as supplementary material. The challenges related to trade-offs were extracted and categorised following a rational decision-making framework, which organises decisions as a 4-step process:

1. **Problem structuring**: clarifications regarding the involved stakeholders; the alternatives, constraints, and uncertainties; the context and the purpose of the decision.
2. **Model building**: the decision problem is formalised by specifying alternatives; defining and prioritising criteria; selecting indicators for the criteria; and modelling uncertainty.
3. **Using the model**: alternatives are evaluated against the chosen criteria, based upon the synthesis of information and the evaluation of indicators, with sensitivity and risk analysis.
4. **Implementation:** after a decision, the solution needs to be planned, executed, and monitored.

The work of Parnell et al. (2010) on the 4-step process of problem solving in systems engineering and Belton and Stewart (2002) 5-step multi-criteria decision-making process were particularly influential for the development of the framework. Rational decision making was chosen as the backbone of the framework because 1) it is easy to understand, 2) it is widely used in science and business, and 3) it is the basis of many of the decision support tools that can be used in trade-off situations.

After data extraction, the challenges were clustered into 23 final issues and evaluated in three 2-hour meetings with experts from industry and academia: 1) manufacturer in the water industry (in-person, 8 participants, including project managers and R&D engineers); 2) industrials and academics from technology and innovation management (online, 10 participants, including researchers and project managers); and 3) academic experts in design for sustainability (in-person, 2 participants, university professors). The experts were shown the identified challenges and asked to evaluate their completeness, relevance, and clarity, reflecting on their occurrence within sustainability-related decisions.

4. Results: trade-off challenges in early design for sustainability

The identified challenges are described in this section, organised per phase of the decision framework, followed by a description of *overarching* challenges. The number in brackets for each table indicates how many times the challenge was mentioned in the sample.

4.1. Problem structuring

Table 1 describes the challenges in the problem structuring phase. Most of the issues are related to building a shared understanding of the problem - what are the goals, the criteria, the alternatives, the assumptions, who are the decision makers and the stakeholders? Experts from industry and academia, saw these challenges as very relevant for sustainability trade-offs, as they precede and form the basis for the whole decision-making process.

Table 1. Challenges when structuring the problem in early design for sustainability

Challenge	Basis in literature	View from experts
Appropriate time and place (3)	Navigating a technical trade-off might also require making decisions at the strategic or business unit level (Kihlander, 2011; Morrison-Saunders and Pope, 2013). There are also often time constraints (Yahaya and Abu-Bakar, 2007).	*"We can sometimes be ahead of competitors and partners sustainability-wise, and that can get in the way"*
Context uncertainties (11)	Uncertainty in external contextual factors might make navigating trade-offs difficult (Bertoni et al., 2020; Ferguson et al., 2023). These factors can be political, societal, related to infrastructure, etc. (Parolin et al., 2023; Wilkof, 1989).	*"Think about the luddites - would someone back then say they were right or wrong? What about now?"*
Defining criteria and constraints (15)	The goals involved in the trade-off must be translated into clear decision criteria (Gustavsson and Sterner, 2008; Oliveira et al., 2012).	*"I wonder if a normative approach, coming from an authority figure, wouldn't be able to solve our problems"*
Defining alternatives (7)	Alternatives might be too dissimilar (Shehabuddeen et al., 2006), too similar (Morrison-Saunders and Pope, 2013), or have different levels of maturity (Kihlander and Ritzén, 2012).	*"When the differences in value chain are too different it might be challenging to perform an assessment"*
Lack shared frame of reference (20)	Actors involved in the trade-off may have different perspectives, interests, incentives, knowledge, expertise, and objectives (Asmone and Chew, 2018; Bekius et al., 2022; Maksimovic et al., 2012).	*"We have a contract about what we need to prove when developing a technology, but it is often broken"*
Identifying strategic goals (9)	The priorities of the company at the strategic level are key influences when navigating trade-offs (Bertoni, 2017; Byggeth and Hochschorner, 2006). The culture of the company also plays an important role (Tonn, 2003).	*"The company prioritises both CO2 emissions and water consumption, but how to balance them?"*

4.2. Model building

Table 2 describes the challenges in the model building phase. The most relevant challenges when it comes to sustainability trade-offs, according to the experts, were related to defining intra-property preferences (e.g., how much increase in energy efficiency can counteract a reduction in recyclability?) and the missing link between characteristics and properties or system-wide consequences.

Table 2. Challenges when building models of decisions in early design for sustainability

Challenge	Basis in literature	View from experts
Dealing with non-negotiable criteria (11)	Trade-offs become unacceptable when there are non-negotiable aspects at play (Lecomte and Blanco, 2015; Tarne et al., 2019), such as legislation, contracts & budgets.	*"What is mandatory and what is nice to have is often not clear"*
Eliciting preferences and weighting criteria (value trade-off) (26)	In trade-offs, one must prioritise between different criteria or define acceptable levels of compromise (Bigolin et al., 2021; Harivardhini et al., 2017; Thurston and Srinivasan, 2003; Vargas-Berrones et al., 2020). Decision makers might be reluctant to assign explicit weights to criteria (Abbas, 2015), and customers might have very different perceptions (Angelo and Marujo, 2020; Bertoni et al., 2015; Shiu, 2015).	*"Sometimes the decision maker is not aware of sustainability, so instead of gathering their preferences, we also need to push the agenda of sustainability"*

Introduction of new constraints or criteria (3)	Preferences and criteria may change over time, as they "evolve and new ones emerge during the design process" (Dwarakanath and Wallace, 1995).	*"New criteria came up every time we had a meeting"*
Lack of methodological support (9)	Decision support tools are either poorly fitted for early design activities (Gould et al., 2017), or not well known or widely used (Gustavsson and Sterner, 2008).	*"We don't have tools to help us perform sustainability assessment"*
Understanding systemic consequences (6)	As stated by Ferguson et al. (2023), the connections between "today's decisions and their full outcome are often difficult to discern and harder to model". Decisions might have unintended consequences, such as burden shifting (Hoffenson and Söderberg, 2015; Serenella et al., 2015) or system-wide effects (Belecheanu et al., 2005).	*"Decision makers often ask themselves is the decision could affect some other overlooked factor. 'What we don't know' is a big factor for them"*
Understanding the link between characteristics and properties (9)	It is not always evident how to tweak a property via design changes (Persson et al., 2021; Thurston and Srinivasan, 2003). Intangible criteria, such as sustainability and aesthetics are hard to quantify and can be highly subjective (Asmone and Chew, 2018; Singhaputtangkul, 2017).	*"We don't know everything when we evaluate sustainability"*
Underestimating uncertainty (2)	Overestimating the level of knowledge might lead to wrong decisions (Abbas, 2015). Over-reliance on modelling requires "the quantification of things that the engineer does not (and likely cannot) know" (Ferguson et al., 2023)	*"Estimates will always lose a comparison with a 'certain' number, like cost"*

4.3. Using the model

Table 3 contains the challenges that arise from using the decision model. Here, there are two main types of issues: those related to performing an assessment (such as lack of data), and those related to actually making the decision after achieving a result (such as having unclear roles). Industrial experts were particularly concerned with communication of sustainability assessment to the (right) decision maker.

Table 3. Challenges when using decision models in early design for sustainability

Challenge	Basis in literature	View from experts
Conflicting results (2)	The same property measured with two different indicators may suggest conflicting results of the trade-off (Kravchenko et al., 2020b).	*"It might actually be helpful, as it prompts you to better understand the problem"*
Data availability and quality (18)	There is often lack of data, uncertainty in what data to use, or low levels of data quality (de Oliveira et al., 2015; Renzi and Leali, 2017)	*"We can never be really sure of the data"*
Interpretation and communication (5)	Some properties or indicators may be hard to communicate (Bertoni et al., 2020) and might be unfamiliar to decision makers (Tarne et al., 2019).	*"We need a common ground of comparison or a common number to translate the sustainability impact to decision makers"*
Multiple decision makers (6)	Design trade-offs may involve more than one decision maker, "from different hierarchical levels, or from different design teams" (Belecheanu et al., 2005).	*"I often do not know who should make the decision"*
Multiple decisions (5)	Trade-offs might often "involve multiple, iterative decisions" (Gibson, 2006).	*"Multiple decisions need to be aligned from technology development to implementation"*

4.4. Implementation

Table 4 contains the challenges from the implementation phase. Even after a decision is initially made and a trade-off is overcome, there can still be issues related to convincing other stakeholders that the decision is sound and worthwhile implementing.

Table 4. Challenges when implementing decisions in early design for sustainability

Challenge	Basis in literature	View from experts
Backpedalling (2)	Actors not originally involved in the trade-off might question the validity of the decision after the fact (Kihlander and Ritzén, 2012).	*"People will often come and say: 'have you thought of this?'"*
Risk and change aversion (3)	Actors might be reluctant to adopt a new, usually riskier, solution or technology. Decision makers might have different attitudes towards risk (Lawani et al., 2023).	*"Risk is a project killer"* *"It may not be the best, but we will go for it because we know it works"*
Limited influence (3)	Certain aspects of the trade-off might fall beyond the authority or influence of the decision maker or the project team (Tonn, 2003).	*"The trade-off might be decided, but the operations department might not agree, and we depend on them for implementation"*

4.5. Overarching challenges

Table 5 contains the "meta" challenges, related to the rational decision making framework itself. The framework is based on key assumptions of rationality, certainty, and the possibility of mathematically modelling the preferences of decision makers, which may not hold true. Experts were particularly concerned with companies not explicitly following a decision making process to begin with.

Table 5. Challenges related to the framework of rational decision making

Challenge	Basis in literature	View from experts
Awareness of decision process (8)	Lack of training in decision making processes (MacKenzie et al., 2020), or resort to intuitive (Yahaya and Abu-Bakar, 2007) or unstructured methods (Gustavsson and Sterner, 2008).	*"There is often no clear decision-making process, or it is very person dependant."*
Bounded rationality (8)	Individuals are not always rational and "may not be able to process all the issues in mind at once" (Singhaputtangkul, 2017).	*"There are hidden criteria that people have but won't or don't know how to share"*

5. Discussion and conclusion

The multiple challenges to successfully navigating trade-offs in early-stage projects can be placed in two main categories: 1) **"soft" challenges**, such as stakeholder management and communication, and 2) **"hard" challenges**, such as modelling of properties, eliciting preferences, and data availability. The literature review was not limited to design for sustainability studies; therefore, these challenges can be attributed to early design decision making in general. This is corroborated by the work of Messerle et al. (2012), who investigated problems of idea evaluation in product development, highlighting the existence of both methodological and organisational types of problems.

However, in reviewed papers that explicitly mentioned sustainability decisions, hard challenges were the most common (e.g., defining, quantifying, and prioritising sustainability criteria, dealing with data uncertainty and indicators). This is somewhat opposed to the view from industrial experts - while they recognized the importance of modelling aspects, they were more concerned with soft challenges, such as communication of sustainability assessment results to stakeholders, making sure all stakeholders are aware of the importance of sustainability, lacking a shared definition of sustainability throughout the company, and understanding systemic influenced and consequences.

Therefore, a clear gap in literature can be identified: how to deal with the "softer" aspects of decision making in early design for sustainability? While more work is needed to create better tools and to understand the modelling and simulation aspects of sustainability trade-offs (de Magalhães et al., 2019), aspects such as communication and stakeholder management seem to be overlooked in current research.

Furthermore, some of the reviewed papers propose potential solutions to the challenges they present. These solutions can also be structured in two main directions: either 1) reinforcing the need and usefulness of a rational decision making framework (with solutions ranging from advanced MCDM tools (Angelo and Marujo, 2020), to probabilistic and fuzzy modelling (Asmone and Chew, 2018), or systems engineering techniques (Bertoni et al., 2018; Hoffenson and Söderberg, 2015), or 2) accepting that decision making in design and innovation is not rational and proposing new approaches (e.g., narrative decision making (Ferguson et al. 2023), naturalistic decision making (Lawani et al., 2023) and future thinking techniques such as future scenarios (Parolin et al., 2023)).

Thus, possible research avenues for trade-offs in early design for sustainability are related to defining and implementing appropriate decision-making frameworks for early design for sustainability in manufacturing companies, which enables the creation of a shared understanding of sustainability at the company, across key stakeholders and decision-makers. It is also important to explore how to define and prioritise sustainability criteria and elicit preferences, considering low data availability and modelling limitations.

This research provides contributions to current knowledge in design decision making by collecting and synthesising the set of trade-off challenges in early design activities, with special focus on design for sustainability. The evaluation by experts points at particularly pressing challenges in design for sustainability that demand further studies. The discussion around "hard" methodological and "soft" organisational challenges is particularly relevant for the complex context of sustainability - the solution to better sustainability decisions may not lie in only in a new lifecycle assessment tool, but in effectively communicating sustainability priorities and preferences, for example. Additionally, the set of challenges may be used to guide the analysis and development of new decision support tools in design for sustainability. The findings of this study can also be timely for engineers and designers as they try to navigate trade-offs in a time of increasing sustainability requirements in product and technology development.

The study has limitations, mainly the scope of the literature review, which was conducted in a single database (Scopus) and only included studies that explicitly stated trade-off challenges. It may be that case studies and other types of reports may also include decision making challenges, but do not explicitly name them as such. Additionally, the use of the MCDM-inspired rational decision-making framework might have biased data collection, as the use of another framework could have led to different set of items. This limitation was balanced by the inclusion of the overarching challenges in section 4.5, related to the framework itself.

Managing trade-offs in design for sustainability is key for achieving innovations that are truly sustainable. This research presents a first step in investigating the existing challenges in sustainability decision making through a systematic literature review and expert evaluation workshops, while also formulating future research avenues.

Supplementary material

Detailed literature review data is available at the following link: http://doi.org/10.11583/DTU.24547738

Acknowledgement

In addition to acknowledging the experts from industry and academia who participated in this study, the authors would like to recognize the support of Manufacturing Academy of Denmark (MADE) through MADE FAST.

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