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A Trade-Off Navigation Framework as a Decision Support for Conflicting Sustainability Indicators within Circular Economy Implementation in the Manufacturing Industry

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Abstract: Integration of sustainability criteria from a triple bottom line perspective is considered a challenge for manufacturing actors, who are engaged in developing sustainability-oriented initiatives. The earlier in the development process the criteria are integrated and sustainability potential is evaluated, the more opportunities exist to introduce improvements and select an initiative with a highest sustainability potential. The challenge does not only lie in understanding what sustainability criteria to use to assess sustainability performance, but in managing conflicting results, known as trade-offs. Trade-offs are situations characterized by conflicts between the desired objectives, where it is impossible to satisfy all criteria simultaneously. Although sustainability trade-offs are common, there is a gap in the existing approaches for sustainability measurements to support trade-off dialogue and decision-making. If trade-offs are not acknowledged, there is a risk of accepting an initiative leading to sub-optimizations or higher impacts. Therefore, this study proposes a framework to support trade-off analysis in the early development stages of sustainability-oriented initiatives. The trade-off navigation framework relies on input data and a structured guidance, with the twofold objective: (i) help making trade-offs explicit, and (ii) provide a structured approach to support trade-off analysis and acceptability in a transparent manner. The purpose is to encourage a dynamic decision process and reinforce the knowledge of decision-makers about potential risks and opportunities behind their choices. Using a case of a product development involving CE principles, this paper discusses how a trade-off navigation framework was applied and evaluated by industrial and academic experts, leading to its improvement and identification of strengths and limitations.

Keywords: circular economy; sustainability indicators; triple bottom line; trade-offs; decision support; early development stages; business process

1. Introduction

In today’s competitive and unpredictable markets, manufacturing companies are seeking innovative ways to transform their businesses to satisfy customer needs while sustaining long-term financial advantages and reducing environmental impact [1], ultimately striving to contribute to sustainable development. Transition to a circular economy (CE) is seen as one of the most powerful ways for business to innovate to achieve competitive advantage by building environmentally and socially resilient systems [2]. CE implies a systems perspective, where production and consumption systems both need to be redesigned to function in a circular way, which aims at eliminating waste, minimizing pollution, and retaining value of goods in the system for longer [3]. For the manufacturing industry, accordingly, it requires simultaneously engaging multiple business processes, including business models, product and service design, forward and reverse logistics, manufacturing, and others, to develop and implement a CE initiative [4].
For a CE initiative to contribute positively to sustainability, triple bottom line (TBL) considerations (i.e., economic, environmental, and social aspects as elements of operational sustainability) should be embedded in early stages of its development [5]. A variety of new metrics and approaches to measure CE have been proposed [6]: some focus on measuring economic value of recirculated products and materials [7], others focus on measuring virgin material input as a degree of product’s circularity [8]. Although new methods and indicators to measure CE are being increasingly proposed [9], it is questionable to what extent they can be used to understand environmental and economic potential of proposed CE initiatives [10]. Ref. [11] reports that the use of re-treaded tyres, while increasing the degree of product’s circularity, increases fuel consumption of a vehicle, hence does not contribute to overall resource savings. Similarly, Reference [12] argues that reuse strategy might not always be more environmentally friendly for electric and electronic goods due to rapid advancements in energy efficiency. Despite there being studies that highlight economic and environmental benefits of CE initiatives compared to non-CE ones [13,14], a case by case assessment is needed [15]. Questioning the applicability of CE-oriented metrics and approaches for the assessment of environmental and economic benefits of CE, the applicability of existing environmental and economic assessment methodologies was investigated [16,17]. In summary, several challenges exist: firstly, none of the analyzed methodologies, including a life cycle assessment (LCA), seem to assess the impacts of CE initiatives that concern redesign of business models for a shared or access-based product use or service provision [17]; secondly, many methodologies do not go beyond the assessment of material and energy parameters [16]; thirdly, the lack of assessment from a social perspective is missing [18], yet alone the assessment from a holistic triple bottom line perspective [19]. The holistic TBL assessment is not only needed to document the impact of CE implementations [5], but to support the development stages of CE initiatives for early assessment of CE potential and possibilities of introducing improvements [20]. Indeed, business model and product development are seen as driving processes to enable CE development [21]; additionally, other operational business processes might need to be considered to support CE implementation [22].

To ensure a holistic sustainability consideration during CE initiative development and avoid sub-optimizations (or even more severe sustainability impacts), high importance economic, social and environmental criteria of the TBL approach need to be integrated early in business processes along the key CE and traditional criteria [5]. The inclusion of TBL criteria increases complexity during decision-making, and while techniques based on qualitative or quantitative indicators to support their measurement exist [23], they lack to provide support for conflicting TBL indicators, known as trade-offs [24,25]. This gap highlights the lack of attention to trade-offs between TBL indicators, despite the evidence that integration of the TBL perspective as a sustainability-oriented decision support would always involve trade-offs [26], either between or within the TBL dimensions [27]. Decision support is needed to ensure that adequate information is used to enable practitioners making informed decisions by explicitly analyzing the existing trade-offs in light of contextual settings [28]. This could reinforce knowledge about proposed initiatives, potential risks, and opportunities behind their acceptance [29].

In light of the presented, this paper brings forward the need to address a sustainability trade-off challenge, which industrial actors experience when integrating TBL indicators for sustainability measurement of the proposed initiatives, including CE initiatives. Consequently, this study proposes a trade-off navigation framework (TONF) to support decision-making between conflicting sustainability indicators in a structured and transparent manner. The framework seeks to fill the identified gap by considering multiple sustainability indicators and prioritization principles based on acceptability ranges and their negotiability. The framework incorporates a step-by-step guidance to support industrial practitioners in carrying out the decision analysis between conflicting sustainability indicators. Additionally, it integrates a trade-off matrix to visualize the required input data and record changes along the decision process. The main aim of the TONF is to
create transparency about sustainability trade-offs and support dialogue about the opportunities and challenges of the considered initiatives in light of the revealed trade-offs. By bringing together the theoretical elements of a sustainability assessment, multicriteria decision-making, and psychology, this study advances the discussion on the integration of sustainability into business processes; specifically, this study highlights the disconnection between how sustainability integration should be performed in theory to achieve sustainability benefits and the degree of decision support that tools and approaches offer.

2. Research Design and Methods

The research process followed a step-by-step approach, depicted in Figure 1. Accordingly, the research commenced by developing an understanding whether and when sustainability trade-offs are a challenge, and whether a trade-off support is provided by the existing decision support techniques (Step 1). As the gaps were discovered, Step 2 was set for the identification of the key criteria that could drive the development of a trade-off decision support. A hypothetical-deductive approach was followed throughout Steps 3 to 5 with the aim to propose a trade-off navigation framework (TONF) following the initial set of criteria from Step 2 and evaluate the framework to introduce improvements and test its usefulness [30]. The TONF was developed with the twofold objective to: (i) help making trade-offs explicit, and (ii) provide a structured approach to support trade-off analysis and acceptability in a transparent manner. Overall, the objective was to inform and support decisions during early integration of sustainability indicators in business processes engaged in CE initiative development.

To attain the objective, a number of research methods were employed in the following way:

Step 1 focused on the identification of a need for a trade-off decision support. Initially, the challenge regarding trade-offs became distinctive during the empirical work conducted in the preceding research that focused on the selection and application of relevant sustainability indicators to support development of CE initiatives [20]. Subsequently, a literature review was performed with the aim of exploring whether the challenge of sustainability-related trade-offs, when implementing sustainability considerations during
business processes, is a common challenge in the experience of manufacturing companies. Literature review I, a selective review [31], was performed because it is particularly useful to frame the research problem and clarify research assumptions [32]. The review focused on the studies from the fields of eco-design, sustainable business modeling, sustainable supply chain management and manufacturing to identify challenges relevant for a number of related business processes, such as business modeling (BM), product development (PD) and product-service system design (PSS), supply chain and manufacturing (SC&M). The review focused on the challenges related to the integration of sustainability criteria to support evaluation of a sustainability potential during early stages of the decision process. Therefore, the generic challenges (e.g., time and cost of sustainability evaluation) [33] or challenges related to knowledge generation about sustainability issues and how to transform them into sustainability strategy or objectives [34,35] were not taken into account. As a result, a trade-off challenge was identified as one of the most prominent challenges (as summarized in Section 3). Despite the result, the literature highlighted the gap in the existing tools to support decisions in sustainability-related trade-off situations [24,36].

Step 2, therefore, aimed at consolidating key criteria to assist the development of the TONF. A selective literature review II, similarly to literature review I, was performed with the aim to identify several criteria to act as building blocks for the TONF development rather than provide an exhaustive list of the criteria. The criteria were extracted from the literature from the field of eco-design [27,37] and sustainable supply chain management [38,39] identified in literature review I, as well as normative works on sustainability assessment [26,40]. The review focused on the proposals for dealing with sustainability-related trade-offs during early integration of sustainability into business processes. The proposals were turned into criteria and are summarized in Section 4.

In Step 3, the criteria were operationalized into a first version of the TONF, incorporating input data and structured guidelines as main elements of the TONF as presented in Section 4. The guidelines for a trade-off navigation are built based on some features of multicriteria decision-making analysis and psychology field. Operationalization of the TONF followed the prescriptive approach, i.e., how to operationalize the extracted proposals, which are seen as ‘whats’ of a trade-off management.

In Step 4, the proposed TONF was tested and evaluated by two different expert groups: twelve experts from academia and eight experts from industry with mixed expertise (Table 1). A combination of interviews and a questionnaire were used for evaluation, as they are considered a common resource for gathering data about the outcomes of a theory testing [41]. The following hypothesis was formulated to guide the evaluation: ‘the trade-off navigation framework can support manufacturing companies in making trade-offs transparent and supporting argumentations for trade-off justification and acceptability’.

The experts from industry were selected based on the following criteria: engaged currently or in the past in sustainability-related projects, either as an industrial practitioner or as a consult for industry. The experts from academia expressed their interest in participating in a workshop dedicated to trade-off navigation support. With industry experts, interviews were conducted with the selected participants individually. Each interview lasted for approximately one hour and followed the corresponding steps: (i) presentation of the TONF; (ii) presentation by the respondent about their background and challenge related to trade-offs; (iii) demonstration of the TONF using an exemplary case; (iv) semi-structured interview focused on the evaluation of the TONF attributes and general feedback. After each interview, the participants individually applied the TONF and subsequently filled in an evaluation questionnaire, consisting of 20 questions. The questionnaire served to collect information about respondents’ knowledge area, familiarity with any sustainability-related decision support, followed by feedback on various attributes of the TONF that they had just trialled. The questions were varied, so as to both include closed-ended evaluation, relying on a three- and four-point Likert scales such as “to a larger extent”, “to some extent”, “no support” and “not satisfactory”, “needs improvement”, “satisfactory” and “very satisfactory”, and an open-ended evaluation, in order to gather improvement sug-
gestions. For the academic experts, the workshop was designed to compare two decision processes—one without and one with the proposed TONF—using a simplified exemplary case, followed by the evaluation using the same evaluation questionnaire as for the industry experts. In Step 5, the TONF was refined, following the improvement suggestions from the combined evaluation by the industrial and academic experts. The final version of the TONF is presented in details in Section 4.

Table 1. Trade-off Navigation Framework, TONF, evaluation experts: industrial experts and academic experts.

<table>
<thead>
<tr>
<th>Expert ID</th>
<th>Area of Expertise</th>
<th>Level of Experience</th>
</tr>
</thead>
<tbody>
<tr>
<td>IA#1</td>
<td>Product design, LCA modelling</td>
<td>&gt;5 years</td>
</tr>
<tr>
<td>IA#2</td>
<td>Product design, manufacturing efficiency, circular economy design</td>
<td>&gt;5 years</td>
</tr>
<tr>
<td>IA#3</td>
<td>Product design, circular economy design</td>
<td>&gt;2 years</td>
</tr>
<tr>
<td>IA#4</td>
<td>Mechanical and environmental engineering</td>
<td>&gt;25 years</td>
</tr>
<tr>
<td>IA#5</td>
<td>Health, quality and safety management, risk management</td>
<td>&gt;2 years</td>
</tr>
<tr>
<td>IA#6</td>
<td>Product design, LCA modelling</td>
<td>&gt;5 years</td>
</tr>
<tr>
<td>IA#7</td>
<td>LCA modelling, sustainability consulting</td>
<td>&gt;10 years</td>
</tr>
<tr>
<td>IA#8</td>
<td>Environmental management, sustainable supply chain management</td>
<td>&gt;10 years</td>
</tr>
<tr>
<td>AE#1-12</td>
<td>Product design, eco-design, LCA modeling</td>
<td>Mixed</td>
</tr>
</tbody>
</table>

3. Presentation of Common Challenges in Implementation of TBL Criteria in Business Processes and the Prominence of Trade-Offs

Integration of sustainability into decision-making during business processes depends on a variety of so-called success factors, such as top and middle management support and commitment [42], allocation of time and resources [43], knowledge about sustainability issues [44] and ways of translating them into specific requirements [35], availability of tools [33], among others. Despite many businesses in Europe having defined their sustainability agenda at the strategic level [43], integration of sustainability into tactical and operational levels is still a challenge, for both large companies, as well as small and medium sized enterprises (SMEs) [45,46]. This can be related to the complexity of criteria that decision-makers at tactical and operational levels are dealing with—adding high relevancy environmental, economic, and social criteria along key business, technical, functional, legal, and customer requirements [23]. Within the TBL criteria, several challenges exist and are prominent for a number of operational business processes. These challenges were consolidated through Literature review I in Step 1, as presented in Table 2.

Challenge nr. 1. describes the difficulty of prioritizing key sustainability issues and related criteria [45,47,48], which can be associated with the lack of knowledge about interconnectedness of sustainability issues (e.g., waste generation) and related criteria (e.g., use of reinforced or mixed materials that are often hard to recycle) or the lack of procedures to support identification of significant issues and aspects [49]. The challenge of balancing sustainability and other (technical, customer) criteria (challenge nr. 2.) arises when optimizing the solution to satisfy both sustainability and other criteria is not possible [33,35,44,50]. One example of such a conflict a manufacturer might experience is a potential to reduce VOC (volatile organic compound) content in their chemical product, however, not doing so because such reduction complicates the use of the chemical by the user, which might affect user satisfaction [51]. This challenge exemplifies a conflict between sustainability criteria and customer criteria. Another challenge is related to understanding how to select relevant sustainability indicators (nr. 3.) [28,52] or measurement methods to quantify sustainability [34,53], which could signal about either the lack of support available in industries to systematically select relevant sustainability indicators among
hundreds of potentially applicable [20] or uncertainty about suitability of some methods for sustainability measurement in the early stages (e.g., diametrically opposite views on suitability of LCA for BM measurement as in [54,55]; or for PD as in [35,56], or for logistics planning as discussed in [53]). Application of sustainability indicators requires setting up a procedure to collect relevant data. However, there is a challenge related to the uncertainty of understanding what data to use for sustainability measurements and how to verify data quality and reliability (nr. 4.) [34,45]. Firstly, this issue can be attributed to the challenge of finding a relevant indicator or a measurement tool (challenge nr. 3.), secondly, to the issues of adding social criteria, which are often qualitative, along more tangible environmental and economic [57]. Thirdly, the challenge (nr. 4.) can relate to the issue of time and cost associated with data collection and verification—use of generic data from databases is commonly a faster and cheaper way of data acquisition, however acquiring data from own operations, suppliers, and users is regarded as more accurate and reliable [58], although costly and time demanding.

Table 2. Challenges associated with implementation of sustainability criteria and the prominence of trade-offs: Note: fr ¹—frequency—number of publications; list of references is provided in Appendix A).

<table>
<thead>
<tr>
<th>Nr</th>
<th>Challenge</th>
<th>Fr ¹</th>
<th>Example</th>
<th>Business Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Prioritizing key sustainability issues and related criteria (e.g., ‘must’ vs. ‘nice to have’)</td>
<td>6</td>
<td>Deciding whether to focus on minimizing CO₂ emissions and energy use or on water scarcity and water use</td>
<td>✓</td>
</tr>
<tr>
<td>2</td>
<td>Balancing sustainability and other (technical, customer) criteria</td>
<td>9</td>
<td>Deciding whether to reduce VOC content in a chemical product which will complicate use of the chemical by the user</td>
<td>✓</td>
</tr>
<tr>
<td>3</td>
<td>Finding a logic of selecting relevant sustainability indicators or measurement methods to quantify sustainability criteria</td>
<td>11</td>
<td>Deciding whether to use generic indicators or (customer, supplier, process) specific indicators; use absolute or relative indicators; find a right balance of indicators across sustainability dimensions</td>
<td>✓</td>
</tr>
<tr>
<td>4</td>
<td>Uncertainty in what data to use for sustainability measurements and data quality</td>
<td>4</td>
<td>Understanding how toxicity is measured; understanding social issues are measured</td>
<td>✓</td>
</tr>
<tr>
<td>5</td>
<td>Interpreting sustainability measurement results to guide decision-making process (e.g., to introduce improvements or show achievement of targets)</td>
<td>9</td>
<td>Understanding whether to focus on reducing the total number of chemical substances in a product or eliminating one chemical</td>
<td>✓</td>
</tr>
<tr>
<td>6</td>
<td>Navigating conflicting sustainability criteria, indicators, and measurement results</td>
<td>11</td>
<td>How to choose: increased durability compromises recyclability; sourcing of a recycled material increases transportation fuel use and costs</td>
<td>✓</td>
</tr>
</tbody>
</table>

The ability of decision-makers to generate knowledge about relevant sustainability issues and use this knowledge as a feedback loop to guide decision-making implies that they can interpret the results of sustainability measurements; however, this is frequently reported as a challenge (nr. 5.) [33,52,59,60]. Few possible reasons for a difficulty in result interpretation could be provided; firstly, it can be related to the unstructured process of sustainability integration, where the measurement (or assessment) is done without the explicit link to (what should precede the actual measurement) identification and selection of relevant sustainability issues and criteria, thus creating ‘fuzziness’ in a sense-making process, leading to devaluing sustainability assessment results [46,61]. Secondly, because of the complexity of the results generated by certain mathematical tools or software, which are not easily pointing out at the improvement opportunities (or rather who should be using the result to indicate improvement opportunities) [59] or requiring an analytical expert to clarify the results [62], which can further be exacerbated by the lack of knowledge of sustainability issues by decision-makers who are the direct users of the results.

Additionally, practitioners experience challenges, when navigating conflicting results, i.e., trade-offs (nr. 6.). Trade-offs are situations characterized by conflicts between the desired objectives [27], where it is impossible to satisfy all criteria simultaneously [63]. Trade-offs complicate the decision process, when a decision-making team encounters difficulties in either balancing the key triple bottom line criteria or prioritizing some criteria at the expense of others (ibid.).
To prioritize and balance sustainability criteria, weighting and rating techniques are used, however, often under uncertainty [24,33,64]. Uncertainty results from an unstructured process of working with sustainability criteria, i.e., the missing logic of selecting relevant criteria, as well as not utilizing results of the assessment to support weighting and ranking [62]. Uncertainty also causes decision-makers to resort to simple procedures in decision-making and use ad hoc tactics, e.g., selection of the same criteria used in previous projects or as a result of subjective preferences of the team without strategic, tactical, and stakeholder perspective [65]. This tactic may compromise the decision-makers’ ability to understand trade-offs and manage them along the initiative implementation [38].

CE initiatives, due to their focus on waste elimination and resource preservation, are often seen as initiatives towards improved sustainability [66]. While it is debatable to what extent CE initiatives can address the holistic triple bottom line perspective [3], there is an agreement that environmental, economic, and quality criteria are often considered in the development of CE initiatives [52,67], as CE is being rooted in existing concepts such as industrial ecology, sharing economy, and eco-design [67]. As a result, the trade-offs between the criteria are common. For a TBL consideration, however, a number of criteria for CE development should be expanded to include the social dimension [5]. This leads to an increased complexity, as highlighted earlier by challenge 4. To visualize the trade-off between the CE criteria and TBL criteria, Table 3 presents some of the trade-offs that might arise during the development of a CE initiative. According to Table 3, trade-offs can arise: (i) between sustainability-related and other (e.g., technical, quality) criteria; (ii) between sustainability criteria, for instance, between economic aspect of cost and environmental aspect of selecting a non-toxic material; (iii) as well as within the dimensions either between different aspects, such as selecting a more lightweight durable material, however not recyclable, or within aspects, such as selecting a lightweight material, however containing toxic substances [27].

### Table 3. Examples of trade-offs between circular economy (CE) criteria and sustainability criteria during development of CE initiatives.

<table>
<thead>
<tr>
<th>Development of a CE Initiative</th>
<th>Challenges and Potential Trade-Offs between the CE Criteria (E—Environmental, Q—Quality, C—Cost)</th>
<th>Challenges and Potential Trade-Offs with Added Triple Bottom Criteria (E—Environmental, Q—Quality, C—Cost, S—Social)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offering a leasing scheme for a product (limited time allows to control returns of used products; reduced cost of ‘ownership’ for the customer) [68]</td>
<td>Might require adding/substituting material to increase durability of a product (or parts) leading to increase in development costs and higher (or other type of) resource use</td>
<td>Q C E</td>
</tr>
<tr>
<td>Introduction of recycled content (to reduce reliance on virgin materials) [69]</td>
<td>Might reduce product/part aesthetic quality (leading to customer dissatisfaction) and physical durability (leading to shorter lifetime)</td>
<td>Q E</td>
</tr>
<tr>
<td>Elimination of toxic substances (e.g., from impregnation process) (to reduce contamination of potential recycling flows) [70]</td>
<td>Might compromise durability of the product leading to its premature obsolescence and waste generation</td>
<td>E E</td>
</tr>
</tbody>
</table>

While translating sustainability requirements into ‘traditional’ design and development requirements helps concretizing sustainability criteria (e.g., relating “reduce fuel usage” to “lower car weight” in product design) [71] and ensuring they will be included in the decision-making process, not all sustainability criteria can be directly translated into such specifications [65], which requires a list of additional sustainability criteria to be added as key criteria in the decision process. It can be pointed out that implementation and trade-off challenges arise as a result of a more thorough work with sustainability during
initiative development stages, which in turn could signal about a relatively high maturity of design process to jointly consider sustainability issues to strengthen decision-making processes [72].

The review shows that most challenges are very prominent for all business processes; additionally, it also shows that trade-offs could arise not only when comparing initiatives on the basis of sustainability indicators, but also when prioritizing sustainability indicators. The review also highlighted the gap related to the availability of a trade-off support—whereas sustainability-related trade-offs can be considered inherent in any sustainability-oriented decision-making process [26]; existing tools and techniques do not provide support to decision-makers at tactical and operational levels in navigating complex decisions in sustainability trade-off situations [24,25].

As a result, this study proposes a trade-off navigation framework (TONF) to support decision-making in trade-off situations between sustainability criteria. Due to the challenge reported for a number of business processes, the TONF aims to be rather generic and understandable by practitioners from different business functions. This particularity is essential, when considering that the majority of CE initiatives require involvement of a range of business processes to contribute to its design and implementation [21], therefore it can be expected that the decision support is understood and applied across functions.

4. Presentation of the TONF

4.1. Criteria for the Development

In order to support the TONF development, literature review II was conducted with the aim to identify several criteria. Table 4 presents the consolidated criteria, elaborations on them, and how the criteria were operationalized in the TONF. A detailed presentation of the criteria is reported in a publication by [73]. As seen from Table 4, the criteria were embedded in the TONF by establishing requirements for input data and developing a step-by-step guidance to support decision analysis using the input data. The TONF is presented afterwards with detailed descriptions of the use context, requirements to the input data, and the steps in the guidance.

Table 4. Criteria for the development of a TONF based on key findings from literature.

<table>
<thead>
<tr>
<th>Criteria #</th>
<th>Elaboration</th>
<th>Criteria Embedded in the TONF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre-condition</td>
<td>Input data:</td>
</tr>
<tr>
<td>#1—Reveal trade-offs between and within sustainability dimensions [26,27,44,46]</td>
<td>To reveal trade-offs, a sustainability assessment or performance measurement should be employed, providing results about performance from a three-dimensional perspective</td>
<td>- indicators (or criteria) to cover a holistic TBL perspective (cross and within dimensions) - information about corporate and initiative-specific objectives and targets - multifunctional team of decision-makers</td>
</tr>
<tr>
<td>#2—Provide several prioritization techniques to encourage open dialogue [34,48,51]</td>
<td>Prioritization techniques should encourage open dialogue about negotiable and non-negotiable criteria and facilitate ranking of alternatives</td>
<td>A step-by-step guidance:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#3—Provide rules to evaluate trade-off acceptability [26]</td>
<td>Rules should encourage evaluation of trade-off acceptability</td>
<td></td>
</tr>
<tr>
<td>#4—Easy to use [24,64,74]</td>
<td>Should be easily integrated in the decision process and applied directly by an industrial practitioner in daily routines (i.e., without support of a third-party expert)</td>
<td>N/A - the TONF does not require utilizing programming techniques and requires direct involvement of a practitioners/decision-makers</td>
</tr>
<tr>
<td>#5—Flexible for different business processes (own criteria based on the summary of challenges in Table 2)</td>
<td>Should be rather flexible to accommodate needs of decision-makers in different business processes</td>
<td>N/A - practical examples to support each step of the guidance</td>
</tr>
</tbody>
</table>
4.2. Trade-Off Navigation Framework, TONF—Required Inputs and Detailed Guidance

The TONF consists of two elements, the input data and a step-by-step guidance for trade-off navigation using the input data and a supporting trade-off matrix developed in Excel (Figure 2). Input data element relies on a contextual information, which is needed to support argumentations and decision analysis following the step-by-step guidance; therefore, availability of the input data is a pre-condition to work with a trade-off navigation. A step-by-step guidance provides a structured approach to analyzing trade-off decisions using the information available in the input data. The guidance proposes steps and guiding questions to facilitate trade-off analysis in an iterative manner. The usefulness of the TONF is defined through the following use context:

- Early stages of sustainability-oriented initiative development (e.g., conceptualization stages of business modelling and product development);
- Multifunctional teams (e.g., management, product designers, sustainability managers).

4.2.1. Input Data

Input data are required as they act as a pre-condition to reveal trade-offs and provide visibility of the decision framing to the decision-makers, therefore, are necessary to include in the decision-making process and support trade-off analysis. Input data show what information is required to frame a decision, supported by the corresponding guidance for where to obtain it. Due to the decision-making being a collaborative process, characterized by the complex nature of decisions that are interdependent [75], the information gathering would require time, iterations, and involvement of several decision-makers, such as project leaders and management team, designers and engineers, and environmental or sustainability professionals (Figure 2). The iterations are necessary because decision-making is a process, during which ‘tentative’ decisions, based on the available information, are made until new information emerges to help verify the decision (ibid.). Therefore, the information required would need to be updated anytime a new type of information is available, and the guidance for trade-off navigation facilitates this.

![Trade-off navigation framework](image)

Figure 2. A trade-off navigation framework and its constituent elements: the input data and the step-by-step guidance.

A List of Key Indicators for a Set of Initiatives for Comparison

The ‘success’ of the manufacturing industry in investigating and advancing sustainability initiatives to achieve competitive advantage is directly linked to the contextual settings, i.e., the ability of the industrial actors to exploit internal capabilities and external resources during business processes [76]. In other words, identifying, managing, and
leveraging contextual sustainability criteria during business processes, such as business modelling or product development, are critical in ensuring the alternative initiatives are proposed to solve particular sustainability problems. Sustainability objectives can be understood as statements for what specific problems have to be solved and to what extent and indicate a direction of preference [61]. Driven by the corporate strategic vision and corporate objective [77], the sustainability objectives should be formulated: while the sustainability objectives on a strategic level can be generic (e.g., minimize environmental impact), they should be translated into specific objectives and then into specific criteria to provide guidance and serve as requirements for decisions and actions at tactical and operational levels [78]. Economic, social, and environmental criteria should then be considered during the decision-making process, i.e., during development of alternatives. These criteria can often be expressed as either qualitative or quantitative indicators (Table 5), which serve as decision criteria to guide evaluation of the ‘best’ initiative, i.e., the solution with the highest potential, or performance, of fulfilling the stated objectives (ibid.). Importantly, the criteria and/or indicators need to be (formulated) aligned with the information and terminology used by the actors, who are to be involved in the decision-making [62], because uncertainty about the meaning of criteria and their values can lead to ‘under prioritization’ of the unknown (less known) criteria [79].

In sustainability-related assessments, complementary use of quantitative and qualitative indicators and measures is advisable [80], which provides a basis to assess, compare, and reveal a difference between proposed alternatives. The assessment can concern: (i) comparison between several alternative (design) solutions proposed to reach a particular objective, e.g., comparison of a ‘traditional’ sale-based business model with an ‘access-based’ business model; (ii) evaluation of the degree of improvement between design options for a product, e.g., ‘traditional’ product design versus design following circular economy principles (e.g., bio-based materials) [81]; and (iii) evaluation of performance to drive the objective setting [79]. Therefore, the goal of employing a sustainability assessment early in the design stages is to ensure that performance indicators and measurements could provide early warning and indicate areas to support improvements or point out the ‘best’ alternative, which delivers desired performance on the selected criteria.

### Table 5. Relationships between objectives, criteria, and indicators (based on Shields, Šolar, and Martin, 2002). Corporate values and strategy—approach to sustainability.

<table>
<thead>
<tr>
<th>Decisions and actions</th>
<th>Objective (as a direction)</th>
<th>Criteria (as a concrete aspect)</th>
<th>Indicator (as a measurable support)</th>
</tr>
</thead>
<tbody>
<tr>
<td>- increase product safety OR eliminate toxic substances</td>
<td>Toxicity of a product</td>
<td>Measured by e.g., type and amount of toxic materials in a product (%)</td>
<td></td>
</tr>
<tr>
<td>- increase work safety</td>
<td>Safety at working stations</td>
<td>Measured by e.g., noise levels, physical load index, etc.</td>
<td></td>
</tr>
<tr>
<td>- increase share of products that can be recycled</td>
<td>Product recyclability</td>
<td>Measured by % of recyclable material in a total mass of product</td>
<td></td>
</tr>
</tbody>
</table>

**Guidance for Indicator Selection**

It is necessary to establish a set of key criteria or indicators to cover economic, social, and environmental dimensions. Ideally, a number of criteria should be around 7 and max 10, with more criteria complicating the decision process [79]. Selection of the key criteria should be based on the contextual settings [65], i.e., aligned with the company’s strategy and objective, corporate approach to sustainability, specifics of the products and processes, or driven by the results of past impact assessments [82]. Sustainability criteria can be selected from the existing frameworks, such as sustainability criteria and sustainability compliance index for product development by [78]. As highlighted before, the criteria might need to be expressed as indicators, which allow for more granularity to measure performance on the criteria: criteria ‘resource use’ can be expressed by indicators measuring material use, material sourcing origin, or material toxicity. Several procedures are available.
Acceptability Ranges and Their Non-Negotiability

Acceptability ranges is another input required to support decision framing. In that, this requires information which acts as a support for the evaluation of whether and/or to what extent the proposed initiative is acceptable, whether trade-offs exist and how significant they are and whether they have to be accepted or new alternatives should be designed instead [51]. Negotiable criteria are the type of criteria the acceptable ranges and targets for which are flexible to be adjusted along the decision-making process. Similarly, non-negotiable criteria can be understood as a boundary condition which ‘locks in’ the acceptable ranges and targets, thus helping to rank these criteria as an important priority.

Guidance for Setting Acceptability Ranges and Non-Negotiability

For each indicator (or criterion), acceptable ranges should be specified. Acceptable ranges might consist of a minimum and maximum value that sets lower or higher limits for acceptable performance on the key indicators. Acceptable ranges should be defined considering internal and external sources for sustainability requirements that should guide the decision. The following list of internal and external sources was created to assist definition of acceptable ranges as follows [23]:

- Strategic vision, goals, or project objectives set by the decision-making group (e.g., influenced by past performance impact assessments, trends analysis, dialogues from sectorial associations, market position, etc.);
- Customer and/or stakeholder requirements;
- Technical (and performance) requirements;
- Legal requirements (incl. health and safety, quality) and legal thresholds.

Depending on these requirements, there might only be a lower value, a higher value, or both. Depending on the number of the indicators, sustainability maturity of the company or the early stage of the decision process with limited information, qualitative statements can be used instead of quantitative values [65]. Examples of acceptability ranges for different contextual settings are shown in Table 6. Not all the acceptability ranges might be available at the point of the decision-making, thus, it might be necessary to involve different stakeholders (internal and external) to create the inputs for the ranges, or discuss the ranges inside the project team itself.
Table 6. Examples of acceptability ranges for different contextual settings.

Examples of Different Acceptability Ranges Considering Contextual Settings:
for the Criteria ‘Product Toxicity’ (Measured by Both Type of Toxic Substances and Their Concentration) There Might be Different Limits Set by Two Companies

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Company A</th>
<th>Company B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Acceptable Ranges</td>
<td>Acceptable Ranges</td>
</tr>
<tr>
<td></td>
<td>Acceptable limits:</td>
<td>Acceptable limits:</td>
</tr>
<tr>
<td></td>
<td>the maximum and only acceptable</td>
<td>the lower value is set to 0 and higher value is set</td>
</tr>
<tr>
<td></td>
<td>limit is 0 for both type and</td>
<td>to 4% (of all types of substances, e.g., flame</td>
</tr>
<tr>
<td></td>
<td>concentration</td>
<td>retardants) by total material weight following</td>
</tr>
<tr>
<td></td>
<td></td>
<td>corporate goal to gradually phase out all toxic</td>
</tr>
<tr>
<td></td>
<td></td>
<td>substances</td>
</tr>
</tbody>
</table>

Non-negotiable criteria can be defined following the sources used to define the acceptability ranges as presented earlier. For each criterion selected for the decision process, the classification is based following the logic: negotiable criteria would be defined as the ones with relatively flexible ranges; non-negotiable criteria would be defined as the ones with fixed acceptability ranges. Importantly, the classification of the criteria will not only differ from one company to another, but also within a company, from project to project, depending on the type of sustainability issue and the proposed solution [79]. Grounded in the importance of the contextual settings for prioritization, few questions were proposed to support reflection on the criteria classification, aiming at avoiding ad hoc prioritization (driven by past decisions or a priori values) [65], such as: (i) why is the criterion non-negotiable and what is the reference (source) for that; (ii) how updated is this information? Examples of non-negotiable and negotiable criteria are given in Table 7.

Table 7. Examples of non-negotiable and negotiable criteria.

Examples of Different Acceptability Ranges Considering Contextual Settings:
for the Criteria ‘Product Toxicity’ (Measured by Both Type of Toxic Substances and Their Concentration) There Might be Different Limits Set by Two Companies.

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Company A</th>
<th>Company B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Acceptable Ranges</td>
<td>Acceptable Ranges</td>
</tr>
<tr>
<td></td>
<td>Non-negotiable criteria based</td>
<td>Non-negotiable criteria based on corporate</td>
</tr>
<tr>
<td></td>
<td>on the customer requirements</td>
<td>objective</td>
</tr>
<tr>
<td></td>
<td>the maximum and only acceptable</td>
<td>the lower value is set to 0 and higher value is set</td>
</tr>
<tr>
<td></td>
<td>limit is 0 for both type and</td>
<td>to 4% (of all types of substances, e.g., flame</td>
</tr>
<tr>
<td></td>
<td>concentration</td>
<td>retardants) by total material weight following</td>
</tr>
<tr>
<td></td>
<td></td>
<td>corporate goal to gradually phase out all toxic</td>
</tr>
<tr>
<td></td>
<td></td>
<td>substances</td>
</tr>
<tr>
<td></td>
<td>the minimum and only value is 40%</td>
<td>Non-negotiable based on the requirement of a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>customer</td>
</tr>
<tr>
<td></td>
<td></td>
<td>the minimum and only value is set to 25%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Non-negotiable based on the corporate objective</td>
</tr>
<tr>
<td></td>
<td></td>
<td>replace virgin content by recycled whenever</td>
</tr>
<tr>
<td></td>
<td></td>
<td>possible</td>
</tr>
</tbody>
</table>

4.2.2. A Step-By-Step Guidance for a Trade-Off Navigation

To start the decision analysis and record the decision process, all the information required by the input data needs to be presented. A trade-off matrix was constructed in the Excel spreadsheet, allowing to register all the information. The coding in the matrix was done in a way to highlight which alternative and on what criteria does satisfy (highlighted in green) or does not (highlighted in red) the acceptability ranges. If one or more alternatives satisfy all the criteria, either of them can be selected to proceed for further development. If not all the criteria are satisfied, the analysis and a trade-off dialogue are encouraged following the proposed steps:

Step 1: Analysis of the performance on non-negotiable criteria

In this step, the focus is done on the non-negotiable criteria. All the alternatives should be compared based on their performance on non-negotiable criteria.
A. If two or more alternatives satisfy all the non-negotiable criteria, proceed to Step 2.
B. If only one alternative satisfies all the non-negotiable criteria, proceed to Step 3.
C. If none of the alternatives satisfy all the non-negotiable criteria, i.e., either some alternatives deliver the acceptable performance on some criteria but not the others, or neither of the alternatives deliver the acceptable performance, then all the alternatives should be rejected, unless:

(a) The non-negotiability of the criteria, hence the acceptable ranges, can be re-evaluated, supported by the questions:
   - Are the acceptability ranges too narrow or too broad?
   - Can they be adjusted and how much?
   - What is the aim of the defined acceptability ranges/target? (Does it show a problem/risks or an opportunity? Can it be seen as an approach to balance the objectives? Does it reflect means to achieving a specific goal?)
   - Can we re-evaluate the ranges/target in a dialogue with stakeholders or management?

This step requires returning back to the input data to re-evaluate: (i) acceptability ranges; (ii) number of considered alternatives; (iii) number and type of key criteria for decision-making (Figure 2).

Notably, while in most cases non-negotiable criteria are ‘locked in’, i.e., non-negotiable at the moment of decision-making, their ‘non-negotiability’ can be revisited internally or externally, facilitated by the questions above. The dialogue facilitation is seen as a way to challenge the status quo and encourage information seeking and knowledge reinforcement [79]. For instance, alternative A may produce more noise than alternative B, but if the noise levels for both are within the acceptable ranges, they both qualify as potential alternatives to be accepted for further development. Similarly, alternative A may produce more noise level than B, but also more than acceptable ranges permit. Then, the evaluation should concern the analysis of the degree to which the noise level for alternative A is unacceptable and why. It has been shown that re-negotiations on the acceptability can happen with the involvement of internal or external stakeholders and managers, who will have an influence on the acceptability ranges and who might establish new initiatives to balance the accepted change [85]. As a result of this dialogue, some ranges can be adjusted and the evaluation should proceed as follows:

A. If none of the alternatives satisfies all (adjusted) non-negotiable criteria, none can be accepted as is, requiring improvement or development of a new set of alternatives.
B. If two or more alternatives satisfy all the non-negotiable criteria, the analysis should proceed to Step 2.
C. If only one alternative satisfies all the non-negotiable criteria, the analysis should proceed to Step 3.

**Step 2: Analysis of the Performance on Negotiable Criteria**

In this step, the focus is done on the negotiable criteria. The analysis should only be performed for the selected alternatives from Step 1. To support this step, weighting and ranking matrices were created in Excel sheet adjacent to the trade-off matrix.

A. Select only the criteria for which none of the alternatives meet the performance within the acceptable ranges (e.g., if one criterion is satisfied by all the considered alternatives, it should be excluded from the analysis to simplify the weighting). For the selected criteria, weights should be assigned to them. A weight indicates the importance of one criterion relative to the other under consideration, i.e., a pairwise comparison. It is important to agree on the ranking scale and use it consistently to support the weighting process. A Likert scale from ‘much more important’ to ‘much less important’ could be used to assign priority weights. In doing so, the weights will express levels of trade-offs between the criteria rather than in absolute terms [79].
After weighting, a ranking of alternatives is performed based on their performance and the degree they satisfy the acceptable ranges. Similarly, a ranking scale should be defined, such as 1 to 3, i.e., from unsatisfactory (1), to some extent satisfactory (2), to satisfactory (3). As a result, the weighting score and the ranking score will be combined to show the alternative/s with the most satisfactory scores.

B. Following the results of the weighting and ranking process, a dialogue about the scores and whether they can help provide judgements for the prioritization of one alternative over others is encouraged.

C. Proceed to Step 3.

Step 3: Decision analysis

In this step, it is necessary to reflect back on the selected alternative(s) based on the results in Step 1 and 2. All the criteria, negotiable and non-negotiable, should be considered, to allow decision analysis to be performed in light of potential trade-offs between all the criteria considered [79]. To make a decision, it is necessary to consider all the argumentations and justifications provided during the process. The following deliberations could occur: if the alternative X is accepted—can its performance on the non-negotiable criteria and high priority negotiable criteria compensate for the trade-offs that are accepted? If yes, does it reflect our goals and provide a new opportunity and minimize risks? Can alternative solutions be set up to compensate for the accepted trade-offs?

5. Application of the TONF

In order to validate the proposed framework and evaluate its usefulness, eight industrial experts from the manufacturing industry had the approach verified using a pre-defined exemplary case (example 1a and 1b). Evaluation with the academic experts only involved example 1a. Additionally, one industrial expert had own example through which the framework was tested (example 2). As a result, both examples, 1a and 2, are presented for the application of the TONF below, followed by the summary of the evaluation by the industrial experts and the experts from academia. To allow for a simplification of the decision process, Step 2 of the TONF guidance was omitted in the examples.

5.1. Example 1a: TONF Application to Support Decision-Making with 2 Alternatives

5.1.1. Filling in the Input Data

This example presents a small and medium sized company who would redesign a product, a furniture unit, to substitute the current material with the locally sourced recycled material. The objectives that drive the substitution are to increase reliance on local sourcing and create local jobs and to increase the share of the recycled material content in the product. These derive from the corporate intention to contribute positively to the community by creating jobs and converting waste to a valuable material, following some of the circular economy principles [3]. The company does not have a publicly available sustainability statement and belongs to the industry with no stringent environmental compliance, additionally, the product can be considered simply made of few parts. Following the guidance for setting the input data, the trade-off matrix was filled in the Excel sheet (Figure 3). As shown in Figure 3, seven key criteria were selected to support sustainability performance measurement for two alternatives: Alternative 0 (A0), which represents the current design and Alternative 1 (A1), which represents the proposed design. All the required by the input data information was made available: the performance was calculated for both alternatives and for all the criteria.

The criteria were calculated as indicators using a database of the leading performance indicators for sustainability screening of CE initiatives proposed by [20]. For some criteria, the qualitative assessment was used: ‘yes’ and ‘no’ grading was done for the criterion ‘local supply of materials’ as well as for the ‘toxicity of materials’, which was marked for both alternatives as ‘yes’ to indicate that both are likely to contain hazardous substances according to the REACH regulation. The acceptability ranges were set: due to no established corporate goals or legal requirements, acceptability ranges for some of the criteria were
defined following the results of the performance measurement for both alternatives. For instance, the minimum acceptability ranges for ‘lifetime of a product’ was set to match the current design in order to keep the current lifetime benchmark known to the customer, while the higher value was set to match to the new design, indicating that a slight increase would also be acceptable. Based on the corporate intentions outlined above, the criteria were classified as non- or negotiable (Figure 3, ‘non-negotiable’ criteria column with yellow highlights). After the trade-off matrix was filled, the proposed trade-off guidelines were employed step by step.

Figure 3. A trade-off matrix with input data details and highlights of attended and not attended criteria.

5.1.2. A Step-by-Step Application

Step 1: Analysis of the performance on non-negotiable criteria

The analysis of the performance based on non-negotiable criteria shows that none of the proposed alternatives satisfy all non-negotiable criteria (Figure 4a). Specifically, the new alternative, A1, did not meet the minimum requirement of waste amount converted to recycled material established by the current alternative. The reason for that was lower efficiency of the recycling process due to poor quality of the waste collected locally. Following the guidelines, the list of questions was used to re-evaluate the acceptability ranges and their non-negotiability; particularly, the question “What is the aim of the defined acceptability ranges” was used to reflect on the desired ranges for the criteria ‘waste recycled into material’. The waste was being collected from non-waste designated areas (i.e., beaches, green zones), which contributed to the overall intention of the company to restore the local natural environment. Therefore, the ranges were adjusted so the minimum acceptable value matched the new alternative, A1 (Figure 4b, with adjusted acceptability ranges for criterion ‘waste recycled into material’). As a result, only one alternative, A1, satisfied all the non-negotiable criteria and was the only option that should be considered for further analysis. Therefore, Step 2 was omitted, as only one alternative satisfied Step 1.
Figure 4. The process of renegotiation in Step 1—acceptable ranges for criterion ‘waste recycled into material’ were renegotiated. (a)—above; (b)—below, with adjusted acceptability ranges for criterion ‘waste recycled into material’.

**Step 2: Not applicable**

**Step 3: Decision analysis**

This step included the analysis of only one alternative, A1, involving all the criteria considered in the decision-making. Two criteria (nr. 1 and nr. 6) were excluded from the decision analysis (shaded areas in Figure 5) because they were not satisfied by either of the proposed alternatives. Based on the information in the trade-off matrix, accepting A1 would mean compromising performance on costs and energy intensity. Using A0 as a benchmark, accepting A1 would increase costs by three times and energy intensity by five times. The decision required a dialogue facilitated by the proposed questions in Step 3: if A1 is accepted, can its performance on the non-negotiable criteria compensate for the trade-offs that are accepted? Can alternative solutions be set up to compensate for the trade-offs? Several deliberations occurred during this dialogue, such as whether the cost of materials was primarily driven by the sorting of waste and its recycling process or by adding the reinforcement and forming a new material mix. If it was the latter, a new type of reinforcement could be considered, which would require making a new assessment with an additional alternative, A2, using the same performance criteria. Similarly, several experts proposed to investigate the energy source for the material processing facility and encourage the facility to switch to renewable energy. This could compensate for the high energy intensity of the process for A1.
5.2. Example 1b: TONF Application to Support Decision-Making with 3 Alternatives

Using the same example, a third alternative, A2, was added to illustrate how the decision analysis would develop if another option was introduced. Information about A3 was added to the trade-off matrix as shown in Figure 6. Following the guideline for Step 1 for non-negotiable criteria, it can be seen that A2 does not satisfy the ‘lifetime of a product’ criteria as well as ‘waste recycled into material’. Therefore, it should be rejected unless the acceptability ranges for those criteria can be (again) re-negotiated. Starting with the ‘lifetime of a product’ criteria, the ranges cannot be adjusted based on the stated reference indicating that the benchmark of at least 5 years of lifetime should be sustained. The performance of A2 on the ‘waste recycled into material’ is beyond the established ranges, however the higher value could be seen as desirable, justified by the corporate intention to follow circular economy principles. Despite the possibility of adjusting the ranges for this criterion, A2 does not satisfy the lifetime criterion, whose minimum range cannot be negotiated, therefore A2 could not be considered further in the decision-making.

5.3. Example 2: TONF Application to Support Decision-Making with 3 Alternatives

This example presents a large company who needs to design a customized product, a private plane, for a private customer. The company belongs to a highly regulated industry that needs to comply with safety legislation. Additionally, the product is complex, requires fuel to operate, and consists of thousands of parts. The customization of a product (A1) was based on the customer requirement to increase comfort relatively to a previously owned product (A0), with the comfort defined as a 4 dB decrease of the interior noise level. Using this information, the trade-off matrix was filled in as shown in Figure 7. Initially, two criteria, noise levels and weight, were used by the company to assess how the performance of A1, the new design, would change compared to A0, the benchmark product. The ‘noise levels’ criterion was used as a key criterion following the customer requirement, however, the engineering team added ‘weight’ criterion to assess how the
addition of an insulating material would affect weight. Due to no requirements to either weight or price, no acceptable ranges were added. During the design process, the team reached a prototype which delivered the 3.5 dB reduction of the required 4 dB. The noise reduction was below the required by the customer level, however, the company decided to contact the customer and test the ‘comfort’ level delivered by the prototype. As a result, the noise level was evaluated as ‘comfortable’ and accepted by the customer, thus the decision was taken to proceed with A2. However, the following deliberations occurred after the project was delivered: Firstly, had the engineers not considered the criteria of (insulating) material consumption and its impact on weight, the initial customer request would be satisfied without discussion. Similarly, more criteria could have been considered to understand how the initially desired alternative, i.e., A1, would perform in terms, for instance, its fuel consumption as well as impact the total cost of ownership. Had these criteria been used to show an increase in the total cost of ownership by 35% between A0 and A1 (Figure 7, criteria 3), the negotiations with the customer would have happened to understand to what extent the increase would be acceptable and provide more flexibility to introduce other alternatives. This example has strongly demonstrated the importance of negotiations, the TONF guidance for Steps 1, 2, and 3 relies on.

Figure 6. Decision-making with 3 alternatives—A2, despite better performance on most of the criteria, is likely to be NOT chosen due to its unsatisfactory performance on non-negotiable criteria ‘lifetime of a product’.

Figure 7. Decision-making with more alternatives and criteria being added along the trade-off navigation.
6. Evaluation of the Results and Discussion

These examples have shown how the TONF guidelines utilized input data and the guidance to assist the discussions and provided transparency in trade-off navigation. In example 1a, the guidance for Step 1 supported reconsideration of the acceptable ranges for one criterion, which led to the prioritization of one alternative, A1, over another, A0, based on its acceptable performance on all the non-negotiable criteria. Step 3 allowed to evaluate A1 alternative in light of its potential trade-offs, i.e., whether the acceptable performance on non-negotiable criteria can justify the selection of A1 alternative, despite its compromised performance on several negotiable criteria. Supported by the questions in Step 3, some deliberations in relation to trade-offs occurred: The arguments were used to inquire more information to support a decision or setting new initiatives to mitigate trade-off consequences. Example 1b was set up to illustrate how an additional alternative, A2, despite delivering a better performance on all the criteria except for one, which could not be re-negotiated, could not be accepted, leading the decisions towards potentially accepting another alternative. Example 2 has shown the effectiveness of criteria negotiation with the customer, thus verifying usefulness of the guidelines in relation to encouraging discussion and reflection on the information used in the decision process and its sources.

Supported by the initial hypothesis posited in Section 2, the evaluation with experts indicated that the TONF framework is useful for: (i) facilitating a dialogue about trade-offs acceptability and alternative prioritization, and (ii) creating transparency and traceability of the decision process (Figure 8a–c). Accordingly, the input data and their guidance provided a good overview of the information, required to frame the decision. For instance, the guidance about the number and type of criteria was found useful in “helping to broaden the focus and move away from ‘single-criteria’-driven decisions”.

Usefulness of the guidance about the number of sustainability-related indicators and performance evaluation using both, qualitative and quantitative values, was also highlighted. The trade-off matrix in Excel was found useful in bringing all the information together and providing visualization of the decision process. The step-by-step guidance and corresponding questions were found useful in facilitating the dialogue about priorities, drive set up of the requirements, and make the discussion explicit: “After going through these steps and questions—you know where the problem is. It helps to discuss (our) requirements for (our) concepts. It is a guidance for a conversation”. Particularly, the following observations were made: first, decision analysis (Step 1) starting with non-negotiable criteria was found useful in terms of encouraging priority setting and reflection on it. Notably, for the analysis in Step 1, all the industrial experts preferred to operate with ‘real’ value instead of using a normalization technique (i.e., transforming the original value into a dimensionless score based on how well it meets the acceptable range), as, for instance, Step 2 guides. Although normalization, presented as weighting, and ranking in Step 2 were useful for creating a dialogue for reinforcing priorities between negotiable criteria (distinguishing between ‘desirable’ and ‘nice’ criteria to ‘replace’ or remove some of the ‘nice’ criteria to simplify the process), it was acknowledged that the final score should not be used as a sole factor to make a decision. Therefore, Step 3 could support the final analysis by combining results from Step 1 and Step 2.

Time-efficiency of the approach application was evaluated at low to medium provided all the required data could be obtained fast enough to support the decision. As one of the experts summarized this application: “the tool [TONF] is so great in its outcomes that, again, I believe it must be widely spread as support to organizational practice. Especially if applied in time (which is desirable)”. The approach was also evaluated as generic to accommodate the needs of any level decision-maker.

Several challenges, however, were also highlighted. First, a challenge of information acquisition was mentioned by all the participants. “You have to do your research and survey your customers and stakeholders”, emphasizes one expert in relation to data collection to drive performance measurements and establish acceptability ranges. Data collection requires time, investment, and knowledge, which are seen as generic challenges
manufacturing companies experience when implementing sustainability in their business activities [33]. Second, a challenge of selecting the advisable number of criteria or indicators was mentioned, which, if not supported to be contextually selected, can often lead to the ad hoc prioritization, often based on costs or CO₂ measurements as few of the widely known.

![Figure 8](image_url)

**Figure 8.** (a)-left, (b)-right, (c)-bottom centre. Evaluation provided by the industrial actors (numbers coincide with expert ID from Table 1 in Section 2).

Considering the abovementioned, this approach to decision analysis and trade-off navigation can support early stages of decision-making in situations with conflicting sustainability criteria. Importantly, it intends to encourage dialogue and provide a structured and transparent approach for analyzing decisions and decision context, and not to provide a ready solution for such conflicts. In this way, it allows the decision-makers to “play” with scenarios, as to where different acceptability limits lie and how acceptable the considered alternatives are in light of those.

To indicate the contribution of this study to the domain of sustainability-oriented decision-making, it can be compared to several studies combining sustainability evaluation and decision support, including a trade-off analysis (Table 8). [86] proposed a multicriteria decision-making approach to evaluate and select alternatives of a product design on the basis of four categories qualitatively measured by a number of criteria, such as customer satisfaction measured by ‘attractive design’, manufacturing utilization measured by ‘time needed to produce a product’, supply chain efficiency measured by ‘use of existing suppliers’, and environmental sustainability measured by ‘design for reuse, remanufacture, and recycle’. The approach relies on weighting each criterion against another (pairwise comparison), multiplied by the ‘level of influence’ of the evaluator (e.g., expert from a decision-making team). The more criteria are under the evaluator’s control, the higher level of influence is assigned. By running a mathematical model, the design with a highest score is suggested. The approach by [86], however, does not consider a range of criteria
from the environmental dimension, nor the economic or social; additionally, no guidance is provided how to support qualitative evaluation of the criteria and how to interpret the final scores rather than solely relying on the highest score for design selection.

Table 8. Comparison of works for sustainability-related trade-off support and their fulfilment of research criteria. (Note: – not fulfilled; ~—partially fulfilled; √—fulfilled).

<table>
<thead>
<tr>
<th>Reference</th>
<th>Fulfilment of Criteria for a Trade-Off Decision Support</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>#1—Reveal Trade-Offs between and within Sustainability Dimensions</td>
</tr>
<tr>
<td>Present study</td>
<td>√</td>
</tr>
<tr>
<td>[86]</td>
<td>–</td>
</tr>
<tr>
<td>[87]</td>
<td>~</td>
</tr>
<tr>
<td>[88]</td>
<td>√</td>
</tr>
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</table>

Ref. [87] proposed and tested a multi-criteria index to support eco-design implementation in manufacturing companies. Environmental impact measured by kg of CO$_2$, technical performance and costs both measured by monetary units (Euro), are the three product criteria considered for design evaluation. The authors proposed a step-by-step approach, which considers internal and external drivers and their influence on the three criteria, which allows calculating weights for each criterion. The weights and measures for corresponding criteria are then calculated in a Product impact index, which is expressed in monetary units and used to compare product designs. A strength of this approach lies in the integration of economic and environmental criteria together with technical ones, as well as it encourages improvements based on the results [87]; however, the weakness lies in the missing integration of the social criteria and aggregation of results into a monetary value, which might not be desirable to express environmental and social performance [79].

Ref. [88] developed a life cycle sustainability assessment-based (LCSA) decision-analysis framework, which consists of two parts: (i) application of a LCSA; and (ii) decision-analysis with a five-phase approach. A LCSA is used to generate input data by providing results for economic, social, and environmental impacts. Decision-analysis is then used to assist objective setting, a qualitative evaluation of each alternative’s potential to achieve the defined objectives and rules for trade-off management. The trade-off management encourages balancing the overall environmental, economic, and social objectives supported by acceptability and manageability tests, which assist decision-makers in a dialogue about potential adjustments and management (amelioration) of existent trade-offs. As a result, if no adjustments are possible and trade-offs cannot be managed, the alternatives are rejected managed [88]. The advantage of this approach by [88] is in the iterative nature of the LCSA decision-analysis framework, which encourages returning to a LCSA to adjust or add new input information and then repeat the phases. However, the LCSA decision-analysis framework approach lacks empirical evaluation. In summary, the comparison between the studies (Table 8) highlights the strengths of the present study in relation to (i) addressing a holistic TBL perspective and corresponding trade-offs, (ii) supporting a dialogue for trade-off acceptability, and (iii) ease of use for decision-makers engaged in business processes.

7. Conclusions

This study presented the trade-off navigation framework (TONF) and its constituent elements: input data and a step-by-step trade-off navigation guidance. The research followed a research process driven by understanding the needs and gaps in relation to trade-off challenges and their handling, consolidation of criteria for the development of a trade-off navigation, and a consequent conceptualization, testing, and refinement of the TONF. Based on several literature reviews and expert evaluation for theory-testing, the
TONF was refined to its final version and evaluated by experts as being a useful approach for trade-off navigation and dialogue in industry.

The TONF is proposed with the aim to assist decision-making between conflicting sustainability criteria and should be used during early development stages of sustainability-oriented initiatives, including CE ones. A first element, the input data, provides a detailed overview and a guidance to the adequate information needed to frame a decision. A second element, a step-by-step guidance, guides decision-making by encouraging analysis of the considered initiatives in light of the defined input data. The iterations are encouraged to allow adjustments of the input data, including consideration of new alternatives or other key criteria to support decisions. The evaluation provided evidence that the TONF is useful to support argumentations for the choice of a specific alternative, reinforce understanding of priority areas, and create transparency and traceability of decisions. The improved procedural rationality may help practitioners make informed decisions by explicitly justifying selection and prioritization of particular sustainability criteria, thus reinforcing the knowledge about potential risks and opportunities behind their choices. Consequently, it may not only support selection of the ‘most beneficial from a triple bottom line perspective’ alternative during design and development of circular products, services, and processes, but also serve as a feedback loop to manage conflicting criteria and continuous improvements.

The main academic contribution of this study can be summarized as:

- Advancing the discussion about the importance of supporting sustainability-related trade-offs after sustainability evaluation;
- Consolidation of key challenges in manufacturing industry related to the integration of sustainability criteria in the early stages of business processes;
- Identification of criteria to support trade-off navigation;
- Proposition of a structured approach to trade-off navigation. From a practical perspective, the following can be highlighted:
  - Overview of the information required to frame a decision;
  - A practical and flexible approach to making trade-off explicit based on the contextual information;
  - A structure to support objectivity and traceability of decisions, including re-evaluation of sustainability implications of proposed CE and other initiatives.

However, there are some limitations that need to be further explored in future research, such as: (i) further practical application involving multifunctional teams of decision-makers, engaged in business model, product development, operational activities, supply chain; (ii) further practical application involving more than 3 alternatives; (iii) automating the steps in the TONF guidance to retrieve and update input data; (iv) integrating a simple mathematical model to allow building scenarios based on the most desirable objective or goal; (v) investigating the potential to integrate the TONF into existing methods used in business processes. Currently, this study aims at developing a user guide and improving the trade-off matrix in Excel to support easier operationalization of the TONF in industry.

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Appendix A

Table A1. References for Table 2 in Section 3.

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<tr>
<td>6</td>
<td>[24,33,42,44,45,47,52–54,64,91]</td>
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