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Procedia CIRP 136 (2025) 383–388

www.elsevier.com/locate/procedia

35th CIRP Design 2025

Definition of *value* in the framework of systems engineering design methodologies with aeronautics insight

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Abstract

Value is a polysemic word when used in engineering design, suitable to create fully-optimized entities. However, its multifaceted nature can hinder the development of effective design approaches. To address that, this research aimed at systematically reviewing the value definitions found across literature to establish a common theoretical basis for future value-based design methodologies. Considering the importance of value in the aeronautical sector, this research was performed both from a general viewpoint and focusing only on aeronautical papers. The main result achieved is the lack of a general-valid value definition, requiring deeper investigations of every element concurring to generate value.

Keywords: Value engineering; Product Development; Aerospace; Design.

1. Introduction

The history of *value* started hundreds of centuries ago with two of the greatest philosophers of every time, Aristotle and Plato [1]. That topic also attracted the attention of several economists, who examined in depth the monetary nature of value [2]. The financial characteristic of value represents the most immediate link with the engineering world, due to the economic success sought by every firm. From a practical viewpoint, this achievement is driven by the identification of customers' needs, along with constraining the time and money spent [3]. In this way, it is possible to achieve a desired outcome through performing a series of activities, grouped under the general phrase *Product Development (PD)* [3], whose connection with value lies in the customers' preference for *valuable* products, i.e., easy to purchase and meeting specific needs [4]. The indissoluble relation between value and PD suggests that, to develop an efficient design methodology, a comprehensive definition of this term should be given. However, value is an abstract concept with ambiguous interpretations, compromising its reliability and validity as a measure and making extremely difficult its definition [5]. Specifically, value has been used to enhance mechanical products since the end of the World War II, resulting in a variety of methods belonging to the Value Engineering (VE) and Value Analysis (VA) fields [6]. Despite various attempts of giving a general classification of these approaches by several national and international organizations [7,8,9,10,11], there is no accordance in giving a global definition of value, resulting in engineers and researchers creating design methodologies based on their personal and limited conceptions. The interest of academic researchers for the value in the field of Product Development Process (PDP) increased quite rapidly at the end of '90s. Nowadays, even though it is possible to identify value applications in different fields [5,12,13], to the best of authors' knowledge, only one Systematic Literature Review (SLR) [5] tried to collect and analyze how value is defined in this framework. In spite of the remarkable work carried out, it targeted only the field of Systems Engineering (SE), limiting the power of its outcomes. Many definitions were found in

10.1016/j.procir.2025.08.067

other engineering fields, but none of them could be adopted as a general-true statement, due to their excessive generality, resulting mostly into definitions not capturing all the elements concurring into the generation of value. The consequences of this fragmentation are value-based methodologies reflecting that variety, where researchers selected value drivers not always in a systematic and structured way, with lacking or even conflicting outcomes. Thus, a new SLR is needed, able to enlarge the field of investigation and, consequently, reaching conclusions with a wider validity. Therefore, the objective of the research work here presented is to collect all the academic documents presenting design methodologies aiming at developing products, systems and/or services whose value has been enhanced. The analysis has been focused on papers including any form of definition and explanation of the concept of *value*, in order to answer to four Research Questions (RQs). Specifically, a General RQ (GRQ), trying to seek for a general-valid value statement, was subdivided into three Specific RQs (SRQs), with the objective of easing the answering to the GRQ by addressing focused topics (i.e., Value Drivers (VDs), stakeholders, and value quantifiers). Due to the high number of papers directly linked to the aeronautical field, these RQs were answered not only from a general point of view, taking into account all the papers found, but also limiting the examination to documents belonging to this specific field. To ensure the Literature Review (LR) systematicity, two different analysis approaches were adopted, the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) [14] and Population, Intervention, Comparison, and Outcomes (PICO) [15], to obtain consistent and repeatable results. In this way, the most important outcome achieved is that a general-valid and comprehensive definition of value does not exist neither in literature nor in standards, leading to the urgence of elaborating a shared and complete statement, stemming from the different point of views identified. The paper is structured as follows: after this Introduction (§1), the proposed SLR approach is presented in Material and Methods (§2). Then, a (§3) Bibliometric analysis is carried out, after which the Results and Discussions (§4) are argued. Finally, Conclusion (§5) is presented containing the author's final reflections.

2. Material and Methods

The proposed SLR was performed following a method made up of the following steps: (i) Research Questions (RQs) conception; (ii) relevant literature research; (iii) sources evaluation and selection; and (iv) identification of themes, debates, and gaps.

2.1. Research Question (RQs) conception

This phase is intended to narrow the research space, in order to define a set of focused and manageable subtopics. The approach to be adopted can be thought as an inverted pyramid, going from a very broad research theme to specific questions to be answered through the analyses of the academic documentation. Firstly, one or more research aims are defined as high-level statements setting some preliminary and rough boundaries to the SLR to be carried out. Due to the lack of specificity of the research aims, to make them operational, it is required to identify a series of research objectives, following the Specific, Measurable, Achievable, Relevant, and Time-bound (SMART) principles [16]. Finally, research objectives have to be transformed into open questions, known as RQs, aiming at searching for specific elements to be analyzed during the review process. From an operative point of view, this specific SLR stemmed from a single research aim, that can be summarized as the "value definition in the frame of engineering design methodologies developed for entities characterized by peculiar features". Moving to the selection of suitable research objectives, they were established through the PICO methodology, including the following elements:

- *Mechanical Entities of Interest (EoIs)* (*Population*)
- *Enhancing value* (type of *Intervention*)
- *Aeronautical products and systems* (elements of *Comparison* in regard to the Population),
- *Analysis of value-based methodologies* (*Outcome*)

Focusing on these elements, a set of general and specific RQs can be derived, listed in Table 1.

Table 1. General and specific RQs.

#	Type	Question	Technical aspect
N/A	General	Is there a single, universally applicable definition of value fitting different contexts?	N/A
1	Specific	Which are the value drivers?	Parameters
2	Specific	Which are the stakeholders considered?	Stakeholders
3	Specific	How is value quantified?	Calculations

2.2. Relevant literature research

To answer these RQs, a collection of suitable papers was identified, starting from academic databases conveniently inspected. This query could be carried out only after the definition of *keywords*, shown in Fig. 1 and grouped according to which research aspect they refer.

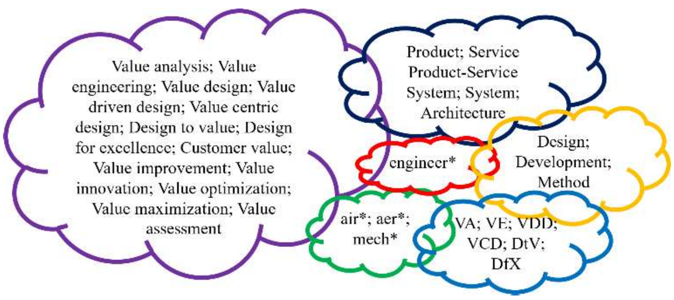

Fig. 1. Cluster of keywords.

The previous keywords were identified in compliance with the PICO categories defined in 2.1, firstly, identifying suitable synonyms for the value methods used to *enhance value* (purple cloud in Fig. 1). Then, the research field was limited on the *product development* (yellow cloud) of *mechanical- and aeronautical-engineering* (red and green clouds) *EoIs* (blue cloud). Finally, acronyms (light-blue cloud) were included, in order to both prevent missing key references and return more precise results. All these keywords were combined with proper Boolean operators to down-select the papers to be analysed in the following SLR steps. Specifically, terms belonging to the same semantic group were used in exclusion (i.e., linked with "OR"), in order not to narrow the research excessively, while the various clusters were linked together through the "AND" conjunction, with the objective of restricting the research boundaries by setting conditions progressively more limiting. These keywords were used to query five databases (i.e., *Scopus*, *Web of Science (WOS)*, *Taylor & Francis*, *Emerald*, and *Institute of Electrical and Electronics Engineers (IEEE)*), selected in accordance with the topics treated and the absence of limitation for the number of Boolean operators allowed for each research. Considering the vastity of the sources catalogued in some of these databases, specific filters were required in certain cases to collect only documents of interest in the circumstance a SLR has to be completed. In particular, only journal and conference papers were considered, written in English, belonging to the engineering sector, and available for the authors carrying out the research process.

2.3. Sources evaluation and selection

All the papers gathered in §2.2 were stored through Microsoft Excel, and duplicates were eliminated (4%). Four Global Criteria (GCs) allowed the authors to reduce the documentation of 78% before starting to read each paper individually. The refinement process ended with the definition of some Specific Criteria (SCs), in order to eliminate documents whose reading did not add any value to the SLR. GCs and SCs (Table 2), led to the selection of 42 papers, listed in the additional materials provided with this paper.

Table 2. Global and Specific Criteria used to refine the sources selection.

Global Criterium	Statement	Type
GC1	No keywords in the abstract	Exclusion
GC2	No keywords in the author keywords	Exclusion
GC3	Not related to mechanical/aeronautical engineering	Exclusion
GC4	Not related to mechanical/aeronautical products	Exclusion
Specific Criterium	**Statement**	**Type**
SC1	Journal paper available with similar/same Conference paper title	Inclusion
SC2	Newer Journal (Conference) paper available with similar/same title	Inclusion
SC3	Out of scope	Exclusion
SC4	Not available	Exclusion
SC5	Not including any value definition	Exclusion

2.4. Identification of themes, debates, and gaps

SLR last step was intended to identify any recurring concept (i.e. *theme*), conflict in terms of methodologies or results (i.e. *debate*), or weaknesses (i.e. *gap*). To check and validate the consistency of the achieved outcomes, the PRISMA 2020 checklist [14] was used at the end of the global analysis, in compliance with the PRISMA principles, used to develop the whole methodology here presented.

3. Bibliometric analysis

The examination of the collected papers started with a bibliometric analysis, with the objective of identifying any trends or divergences from a more general point of view, considering publication years, paper and research types, and belonging fields.

3.1. Years of publication

As depicted in Fig. 2, publication years lay only in the 21st century. No time constraints were defined when collecting the papers in §2, apart from the necessity of setting an end date for the research process itself. The cutoff date was established as December 31, 2023, to provide adequate time for result processing prior to dissemination within the scientific community. This decision aimed to facilitate a comprehensive and systematic review while preventing biases associated with analyzing only quarterly or semiannual data.

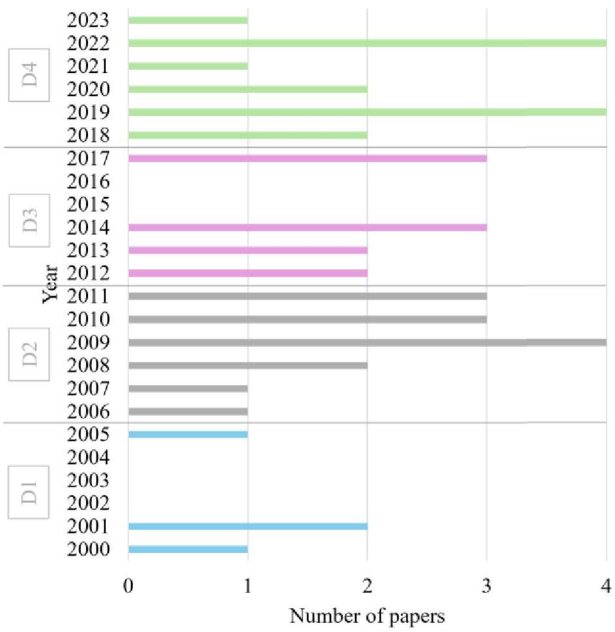

Fig. 2. Number of papers published each year from 2000 to 2023.

From a general point of view, three spikes emerged from this analysis: 2009, 2019, and 2022. To find a justification for these local increases, recurring themes in terms of theoretical basis, methodology, and/or case study were examined. Firstly, two out of the twelve articles are SLRs, published in 2009 and 2019, respectively. This affirms not only the importance of the value topic, considering that the attention of researchers has remained vivid throughout the years, but also the need of carrying out additional investigations, due to the many engineering aspects that value can influence. For the remaining 10 documents, some commonalities in terms of approaches were spotted. Specifically, the Epoch-Era Analysis (EEA) by Ross et al. [18] constituted the theoretical foundation of two of those papers, while other three of them made explicit the usage of VA and VE principles. However, other methodologies could be spotted as well, proving that a variety of methods has been developed so far. Looking at the use cases brought, five documents fell into the aeronautical and aerospace field, whose connections with value has been known since the beginning of the modern value theory. To deepen the bibliometric examination, four clusters (i.e., D1 – D4 in Fig. 2) were defined. Considering the ratio between the number of papers and the length of time period for each of them, the most prolific segments appeared to be D2 and D4, with both ratios of 2.3. For the first time period under examination, the increment in literature production can be motivated by two important events: the launch in 2008 of the Future, Fast, Flexible, Fractionated, Free-Flying Spacecraft United by Information Exchange (F6) System program by the Defense Advanced Research Projects Agency (DARPA) of United States of America [19], and the development of the Value-Driven Design (VDD) methodology [12] in 2009. Whereas, considering D4, in analogy with what discovered for the 2019 and 2022 spikes, four documents directly referred to the VA and VE terms, meaning that researchers were trying to standardize the terminology associated to value design. Minor commonalities were identified in the interest for the application of value to SE and the adoption of VDD principles. From this examination, clear evidence supported the need for a new SLR, as the spread of the same standardized terms (i.e., VE and VA) to present different methodologies, the existence of at least two pivotal studies [12,18] dominating the research field, and the general fragmentation of these studies, generally focusing only on specific aspects (e.g., SE)

3.2. Type of papers

Focusing on the type of sources considered, the majority were conference proceedings (60%). Even though the imbalance is not so pronounced, it still proves that the maturity of the clustered research works is not full, with many ideas stemming from several inputs. This outcome reinforces the need for a new SLR, in order to classify these efforts and define a clear way to aggregate them.

3.3. Type of research

The result obtained in §3.2 is confirmed by the fact that most of the documents collected were original papers (i.e., 25 out of 42), meaning that there is a prolific activity in relation to defining value and its applications in engineering design. In addition, the number of case studies (i.e., 9) is almost identical to the amount of SLRs identified. The main conclusion that can be drawn from that is the need for a systematic classification of all the academic efforts, as well as a considerable lack in term of value applications. Even though it can be found a greater amount of papers (i.e., 37) with case studies practically demonstrating the value-based methodologies that they contain, only 24% started from an explicit definition of what value is.

3.4. Field classification

Figure 3 shows that the fields of applications of value are heterogenous, with eight different engineering sectors for which at least a design methods was defined and value statements were provided.

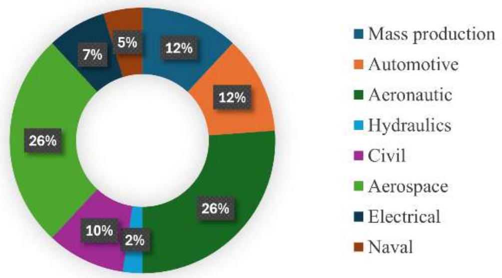

Fig. 3. Engineering fields where value statements and methods are present.

It clearly emerged that value is spread in every engineering field, reflecting the interest shown by researchers and emphasizing the necessity of analyzing the different value definitions and approaches provided, to verify any similarities or discrepancies. From a more specific viewpoint, the aeronautic and aerospace sectors were the most represented, each accounting for 26% of the total. This cannot be considered only as a consequence of the attention paid to the aeronautical field by the presented SLR, since specific keywords for the whole mechanical field were selected. Indeed, the identified trend can be justified looking at the history of value theory, comprising several specific programs put in place in these fields [19,20,21]. For that reason, this SLR was executed also from a specific viewpoint, with comparisons between the general case, comprising all the documentation found, and the aeronautical sector.

4. Results and discussions

To answer to the RQs stated in §2.1, the analysis was carried out from two different perspectives: a general one and focusing only on the aeronautical field, due to the attention paid to this sector, as outlined in §3.4. Firstly, all the value definitions were inspected to identify any repetition. Out of the 42 papers considered, in only two couples value was outlined in the same way, suggesting a lack of accordance between researchers in how value should be defined. Secondly, the issue of providing a unique and comprehensive statement is increased by the fact that the total number of definitions gathered almost doubles the amount of documents examined, testifying the struggle of providing a single and complete statement. The same lack of agreement was identified in the aeronautical field, where the situation worsens, with no shared definitions at all. Considering each proposition in detail, they were inspected to find key terms crucial to characterize what value is and how it can be achieved, i.e., *value drivers*. The process started with the identification of the most recurring keywords, listed in Fig. 4. The top-three terms are either directly related to the entity able to deliver the value (i.e., *system* and *product*) or linked to this aspect (i.e., *function*), showing that, so far, the main concern has been in addressing *what* provides value.

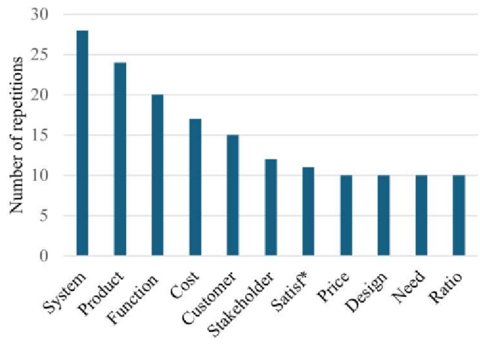

Fig. 4. Keywords repeated at least ten times. The asterisk is used to collect several terms having the same root.

Looking at the words suggesting *how* to numerically define this element, there was a neat prevalence of financial measures (i.e., *cost* and *price*), but it emerged also the tendency of computing value as a balance between various elements, not only with a monetary essence, mathematically represented by a *ratio*. This is the first important discrepancy that can be spotted, since it is recognized that value is a parameter summing up several dimensions, but the only ones made explicit are monetary terms. That issue is even more evident when considering the terms referred to *who* is able to perceive value and their related words. Indeed, value is a matter of *satisfying stakeholders' needs*, that are not related only to the price they have to pay to own the entity providing value for them. However, the definition of stakeholders' and their needs is very general and vague, since *customers* are the only stakeholders outlined, while suggestions in terms of possible needs are given only in a few statements (e.g., *quality*, *utility*, and *benefit*). Finally, a good amount of definitions made clear that value is something that can be achieved and enhanced through the *design* of the end-products, justifying the aim of the presented research work. These trends and gaps can be explained considering the propositions stated by national and international organizations. Specifically, the vagueness of the International Organization for Standardization (ISO) [10] in making clear what value is, even though its proposition is a good starting point, gives so much freedom to researchers and engineers that the unavoidable consequence is a plurality of definitions not always in agreement. More specific attempts were made by the European Committee for Standardization (CEN) [6], the American Society for Testing and Materials (ASTM) [9], and SAVE International® [11]. In these cases, in analogy with the most-recurring keywords in Fig. 4, it was recognized the importance of *what* is providing value and the fact that this is done through performing *functions*. Moreover, in three propositions, value is measured as the ratio between the fulfilment of these functions and the resources consumed to achieve that outcome, even though it is not cleared how to estimate the degree of fulfilment. Looking at the resources, the American standard [9] and definition [11] identify *cost* as a suitable measure, explaining why many researchers selected financial parameters to assess end-product value. However, the CEN clearly disagree with this oversimplification, testifying the importance of extending the analysis to other components, as environment, reliability, and time. From the investigation of all these statements, it is possible to identify three main elements that are part of the value mechanism: (i) *what* delivers value, named *end-product (EP)*; (ii) *who* is able to *perceive* and assess the delivered value, named *enabling system (ES)*; and (iii) *who* delivers value by producing the end-product, named *enabler for enabling system (EES)*. According to the clustered elements, the value definitions were analyzed, counting the number of occurrences for each group on the basis of the keywords found. The results obtained are depicted in Fig. 5-a) for the general case and in Fig. 5-b) for the aeronautical one, proving that there is a neat preponderance on defining value from the end-product (EP) point of view, disregarding the other two elements, resulting in only 13% for the general case and 6% for the aeronautical field of statements addressing all the three clusters.

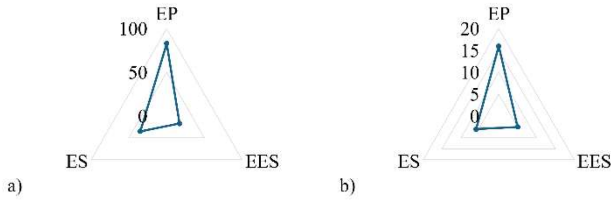

Fig. 5. Number of occurrences for each value element cluster for the (a) general case; and (b) aeronautical field.

Merging this result with the most-recurring term analysis, it is clear that *stakeholders* were not taken into consideration so much, indicating a clear gap into the definition of their influence in the value creation mechanism. Finally, to complete the investigation on how value is computed, all the terms suggesting possible ways of calculation were clustered into two main groups: (i) financial: currency measures as price, cost, etc.; and (ii) non-financial: non-currency measures as quality, utility, etc. The discrepancy between the general (Fig. 6-a)) and aeronautical cases (Fig. 6-b)) demonstrates that value should not be quantified from a mere monetary point of view, especially for complex entities, whose success is likely to be linked to several different aspects.

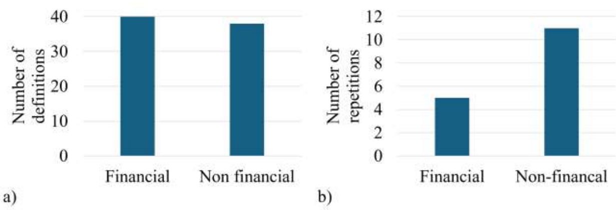

Fig. 6. Financial VS. non-financial value definitions in the a) general case; and b) aeronautical field.

All these elements allow the authors to conclude that a unique and general-valid value definition does not exist, encouraging researchers to pursue this object through focusing on the three value elements with the same effort, taking into account the multi-faceted nature of value. In addition, a deeper analysis should be performed to correctly characterize the stakeholders involved in the value creation process, as well as to include non-monetary aspects in the quantification of the value. The results of these analyses can be used to practically help researchers and practitioners to derive a new value statement, defining it as a hybrid quantitative relationship interconnecting who perceive it with the entities delivering it and the systems enabling this link. The progresses made in this sense are likely to allow to deliver a new value standard, to be widely adopted both in academia and research and encouraging the development of more impactful value-driven design methodologies, able to optimize EoIs from a holistic viewpoint. The outcome of these desired implications will be a more efficient and streamlined design optimization process, with potential outlooks including enhanced decision-making, reduced costs, and improved overall system performance.

5. Conclusion

The presented SLR was accomplished by following a structured methodology combining PRISMA, PICO, and SMART principles. Four RQs were used to guide the selection of 42 papers, using suitable keywords and refinement criteria. The documents were initially analyzed for publication years, paper and research types, and belonging sectors. This resulted not only in the justification of the necessity for a new SLR, but also in identifying pivotal studies and recurring theories, not always in accordance. Given the importance of the aeronautical field, a dichotomic approach was taken, comparing the global results with the ones achieved focusing only on the aeronautical papers. The detailed analysis addressed each RQ, leading to four main issues (I):

I1 - A unique and general-valid value definition does not exist, especially if considering the aeronautical field. Disagreements in literature are likely to stem from discrepancies affecting the standards analyzed. This is a result of the polysemic nature of value, which is composed by so many and varied drivers that researchers are struggling to aggregate them into a full and operative definition, ending in partial and biased statements.

I2 - Most of the statements focus only on the end-products and not on the elements able to perceive their value. The most important aspect that is not properly tackled is the subjectivity nature of value, due to the lack of consideration for stakeholders. Value exists only if there is someone able to assess it.

I3 – The vague definition of stakeholders is demonstrated by the fact that *customers* are the only ones explicitly appearing, indicating a clear gap. Customers are only an example of possible product users, along with the fact that stakeholders comprehend also manufacturers, sellers, and any other people that contributes to make each end-product available.

I4 - There is no agreement on how to compute value, even though many definitions tend to associate it with monetary parameters. However, this is not true if only the aeronautical field is considered, suggesting that value should not be reduced to a mere matter of prices or costs, especially for complex products involving several parameters and stakeholders.

Different actions are needed to solve these important criticalities. Firstly, all the elements involved in the value process should be considered, especially the stakeholders (both *enabling systems* and *enablers for enabling systems*). The proper identification of all the Value Drivers (VDs) will clarify the multifaceted nature of value, whose quantitative assessment should comprehend aspects beyond financial ones. To obtain this information, additional research works have to be carried out, including brainstorming sessions, interviews, and surveys to catch the knowledge and preferences of every stakeholder involved. Additionally, more case studies should be considered to capture the variety in value perception. Finally, it is recommended to extend this research to the value approaches elaborated, with the aim of developing a new methodology rooted in a solid, shared and standardized value statement.

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