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How can technology assessment tools support sustainable innovation? A systematic literature review and synthesis

Giácomo Parolin [*], Tim C. McAloone, Daniela C.A. Pigosso

Technical University of Denmark (DTU), Department of Civil and Mechanical Engineering, Kgs. Lyngby, Denmark

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ABSTRACT

Sustainability considerations are increasingly important for manufacturing companies seeking to develop products that meet the needs of society and the environment. The way technologies are assessed in the early design stages plays a crucial role in the integration of sustainability into innovation activities – a necessary step towards the development of products and processes with better environmental and social consequences. However, existing sustainability assessment tools are difficult to deploy in the highly uncertain and data-scarce front-end of innovation. In order to ascertain the efficacy of technology assessment methods, a systematic literature review was conducted to systematize best practices in technology assessment and establish a set of design propositions to improve early-stage sustainability assessment. Subsequently, recommendations for designing and effectively implementing sustainability assessment tools in technology development were elicited. Several avenues for future research are proposed, including the testing and refinement of the design propositions and how to operationalize early-stage sustainability assessment.

1. Introduction

Technology development is a critical phase of the innovation process in manufacturing companies (Gaubinger and Rabl, 2014) that can significantly impact a product's sustainability performance across its life cycle (Chebaeva et al., 2021). Technology development projects are foundational to a company's portfolio (Cooper, 2006), giving rise to multiple potential commercial offerings, through new product capabilities and functions, new concepts and architectures, or novel production processes. Therefore, technology research and development (R&D) projects, as early design activities, have disproportionate impact in the sustainability performance of a company's business (McAloone and Pigosso, 2018). Decisions and assessments made in technology development have major influence on the future environmental, economic, and social impacts of technologies, processes, and products (Fisher and Rip, 2013).

Technology assessment (TA) is an essential part of the technology development activities. TA is a systematic approach to evaluate the technical feasibility, economic viability, and societal impacts of new technologies and innovations (Rip, 2015). Companies often need to make decisions about which innovation projects to engage in, even when little information is available (Mitchell et al., 2022). Thus, technology assessment methods have been widely applied in manufacturing companies to inform decision-making and optimize R&D investments (Rip, 2015; Tran and Daim, 2008). TA can be applied in various stages of technology development or even repeatedly in the same project, depending on how the design process is structured (Aristodemou et al., 2019). In addition, TA can be useful in opportunity scoping, idea selection, project planning, and iteratively applied as the technology concept is further developed (Gaubinger and Rabl, 2014).

As sustainability has become an increasingly important consideration in innovation activities, manufacturing companies aim to integrate sustainability into their technology assessment methods to address potential future environmental and social impacts (Farrukh and Holgado, 2020). Sustainability assessment (SA) is an umbrella term for the set of appraisal methods, often complex and multidisciplinary, which seek to support decision-makers on which actions they should take, towards a more sustainable society (Sala et al., 2015). Several SA methods exist, which are routinely used by manufacturing companies to evaluate the sustainability performance of products, examples of such including life cycle assessment (McAloone and Pigosso, 2018) and ecodesign tools (Pigosso et al., 2015).

While there are similarities between TA and (product-focused) SA methods, there are also significant differences (Chebaeva et al., 2021).

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[*] Corresponding author. Koppels Allé, Building 404, DK, 2800, Kgs. Lyngby, Denmark.
E-mail address: gipar@dtu.dk (G. Parolin).

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Four challenges for applying SA in early-stage technology development and innovation have been identified (Parolin et al., 2023), namely: (i) lack of data regarding low-maturity technologies; (ii) breadth of scope as projects can vary greatly in goals and maturity; (iii) context uncertainty given that a technology's degree of sustainability is highly dependent on its application and future socio-technical factors; and (iv) competing interpretations of the concept of sustainability at the operational level. For these reasons, conventional SA methods aimed at product appraisal can often fail when applied to early-stage innovation projects.

Therefore, in this paper, we review TA methods and subsequently synthesize actions that manufacturing companies can adopt to improve their SA tools for innovation, ultimately enhancing the sustainability performance of their technologies, products, and operations. We adopt a Design Science (DS) approach (Romme and Holmström, 2023), due to its relevance to the development of tools that bridge the gap between theory and practice (Schutselaars et al., 2023). Via a systematic literature review, existing TA methods are categorized, analyzed, and best practices are synthesized as design propositions (Romme and Dimov, 2021). With a problem-focused methodology (Romme and Holmström, 2023), actions and possible mechanisms are proposed for practitioners to apply when performing sustainability-driven TA and for scholars to explore when developing new SA tools for early-stage projects.

In the following section, the systematic literature review methodology is described, including study selection and analysis. Next, the findings are presented, which highlight characteristics of existing technology assessment methods and their relation to sustainability assessment. Based on these findings, a set of design propositions to guide SA application in technology development are highlighted. In the discussion section, possible mechanisms for the design propositions are tentatively explored and the findings are contextualized within the existing literature on SA. Finally, the paper is concluded by summarizing the key contributions and discussing avenues for future research.

2. Methodology

This study consists of a systematic literature review (de Almeida Biolchini et al., 2007) with the goal of collecting and analyzing existing methods for conducting technology assessment in an industrial context. Following a DS-informed methodology, research was synthesized into *design principles* (Denyer et al., 2008) for technology assessment tools in practice. DS has been proposed as a useful approach for linking theory and practice when addressing multifaceted challenges (Schutselaars et al., 2023), including the development of tools for sustainability-related issues (Romme and Holmström, 2023). The ensuing subsections describe the review and synthesis process, following the PRISMA framework (Page et al., 2021). The complete search strategy and literature review protocol can be accessed in the supplementary material.

2.1. Literature search

The search was conducted in Scopus and Web of Science databases. Both databases have a broad indexing of technical and socio-technical literature in the fields of sustainable design, management, and innovation. The search strategy was built around relevant keywords based on the aim of the review: *technology development*, *assessment*, *tool*, and *innovation*. Search strings were developed for each keyword, grouping related concepts and synonyms with "OR" logic connectors (Table 1). Finally, the four strings were combined into one with "AND" connectors. Since the goal was to achieve a broad mapping of technology assessment methods, the search strategy was not restricted to sustainability-related approaches or to specific publication dates.

2.2. Study selection and data collection

The initial pool of studies was screened for duplicates and for relevancy. Included studies presented methods, tools, indicators, or any approaches designed to assess or evaluate technologies during early development activities in industrial settings. Articles of other fields such as medicine or pharmacy (where *health technology assessments* are often conducted) were excluded. Studies focused on the public sector and policymaking were excluded, as the review only related to industrial innovation. Simple viability studies in the chemical or process industry were also excluded since they cannot be easily transposed to other industrial contexts. Life Cycle Assessment papers which did not stray away from their traditional process or did not implement any new methodological feature were excluded due to their retrospective nature, which is unsuitable in early development activities (Villares et al., 2017). Additionally, when a selected study was primarily review-based, other articles from its references were analyzed for inclusion (also referred to as *snowballing*). The selected articles were read in full and data on TA and SA methods and tools presented in the studies were extracted and logged.

Table 1
Search strategy. Each string was combined with "AND" connectors.

Keyword	Searched fields	Search string
Technology development	Title, Abstract, Keywords (Scopus) All fields (Web of Science)	"front-end" OR "frontend" OR "techno* development" OR ″R&D*" OR "research and development*" OR "early-stage*" OR "industrial research" OR "emerging techno*" OR "innovation project*"
Assessment	Title	assessment* OR analys?s OR evaluat* OR estimat* OR selection* OR measur* OR appraisal* OR audit* OR choice* OR "scor*"
Tool	Title	tool* OR method* OR framework* OR technique* OR approach* OR method* OR initiative* OR strateg* OR guideline* OR indicator* OR integrat*
Innovation	Title	techno* OR innovat* OR invent*

2.3. Method analysis

To characterize the selected TA methods, all authors analyzed the extracted data to look for commonalities and differences among (categories of) methods. Special focus was placed on understanding the gaps in sustainability-related methods, compared to other technology assessment tools. All data analysis was performed using Microsoft Excel. Each method or tool (henceforth only referred to as *method*) was analyzed according to the parameters or virtue (e.g., cost, quality, efficiency) being assessed, building on top of Olesen's universal virtues framework for products (Olesen, 1992). Additionally, methods were characterized according to industrial sector; type of technology (if aimed at product or process); stage of development process; data requirements; time requirements; type of intended user (expert or novice); presence or absence of sustainability concerns; presence of scenarios, number and type of indicator used, presence of multi-criteria analysis, type of implementation (software or workshop), and presence of uncertainty considerations. Findings are shown in section 3.

TA methods were examined following a synthetical approach according to DS methodology (Denyer et al., 2008). The methods were surveyed for practices that could guide the implementation of TA in industry. These *best practices* are also called *design principles* or design *propositions,* and they can be used to direct the development and deployment of SA into technology development and other innovation activities. Design propositions are common artifacts resulting from DS-informed literature reviews (Bhatnagar et al., 2022), which aim to connect science and design, or retrospective and prospective knowledge (Romme and Dimov, 2021). They are often phrased in a Context-Agency-Mechanism-Outcome (CAMO) or Context-Intervention-Mechanism-Outcome (CIMO) logic format, acting both as descriptive-explanatory and prescriptive-normative statements (Romme and Dimov, 2021). In this article, *design propositions* are discussed to clearly differentiate them from *design principles*, since they are only initial proposals which have not been tested.

The DS-informed literature synthesis approach employed in this study is illustrated by Fig. 1. To extract design propositions from the literature review findings (indicated by number 1 in the figure), methods which were tested in practice (number 2) were assumed to be more effective than untested ones (3). A method was considered as tested in practice when the study included at least one industrial case or real application, as opposed to only hypothetical cases or simulations. Bearing in mind this assumption, it is then possible to define which characteristics are disproportionately present in effective technology assessment methods (i.e., best practices, number 4). These characteristics are then formulated as the Context and Action/Intervention of a design proposition (5), presented in section 4.

The Mechanisms and Outcomes related to these Actions were often not present or not clearly stated in the original studies. Therefore, tentative explanations for the Actions are proposed and discussed in section 5, substantiated by management and innovation studies literature (not originally included in the scope of the systematic review). Via abductive reasoning, these sources are used to hypothesize possible mechanisms that may explain why certain actions lead to more effective TA methods.

3. Findings

Initial search in databases resulted in 1984 unique studies, out of which 168 were included in the review. See the supplementary material for complete description and flow diagram of the search and screening process. The 168 papers were analyzed in depth and 170 technology assessment methods for industry were identified. This section presents results from the analysis by describing characteristics of the methods, commonalities, and differences between them, as well as their relationship to sustainability. Methods are identified by an alphanumerical code with the format [M000]. The mapping of method code to source (study) is available in the Appendix.

3.1. Summary of technology assessment methods

The majority of the 170 analyzed methods deal with technologies for product innovation (n = 67) or process innovation (n = 72), while only one is aimed at digital technologies specifically. Some authors claim their methods can be used for any type of technology (n = 22) and a few studies have indeterminate application (n = 8). The assessments span from complex mathematical simulations of fuel synthesis [M155] to simple qualitative checklists of product viability [M103]; and very specialized multi-indicator assessment of biochemical methane generation technologies [M134] to very generic and accessible scoring of innovation projects [M157].

Methods were also sorted according to the main industrial sector where they can be applied, based on the classification from European Union's Directorate-General for Internal Market, Industry, Entrepreneurship and SME (European Commission, n.d.). Most product-related technologies are applicable to Mechanical Engineering industries (n = 21) followed by Electric Electronic (n = 13) and Automotive (n = 12). Process-related technologies are predominantly useful for Chemical (n = 23) followed by Mechanical Engineering (n = 22). The breakdown of type of technology contemplated by assessment methods in each industrial sector is shown in Fig. 2.

Moreover, methods were categorized according to the virtues (Olesen, 1992) or parameters that they can assess in a technology (Fig. 3). Most methods included business metrics, such as financial measures (n

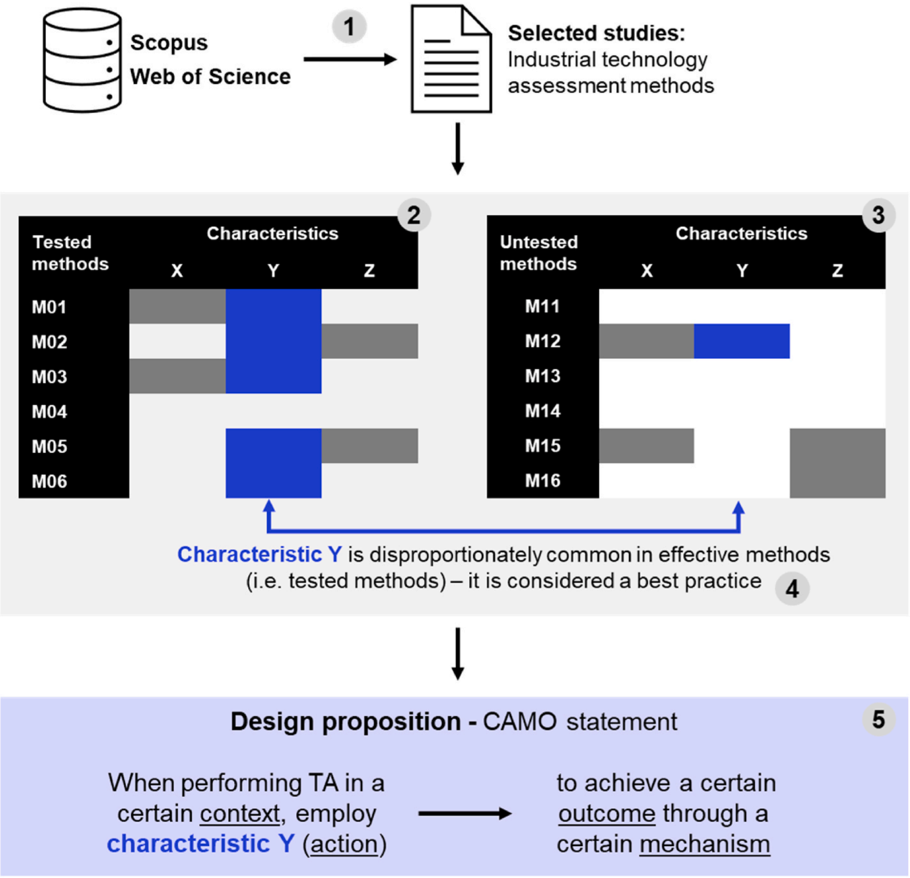

Fig. 1. Literature synthesis approach: extracting design principles from a systematic literature review.

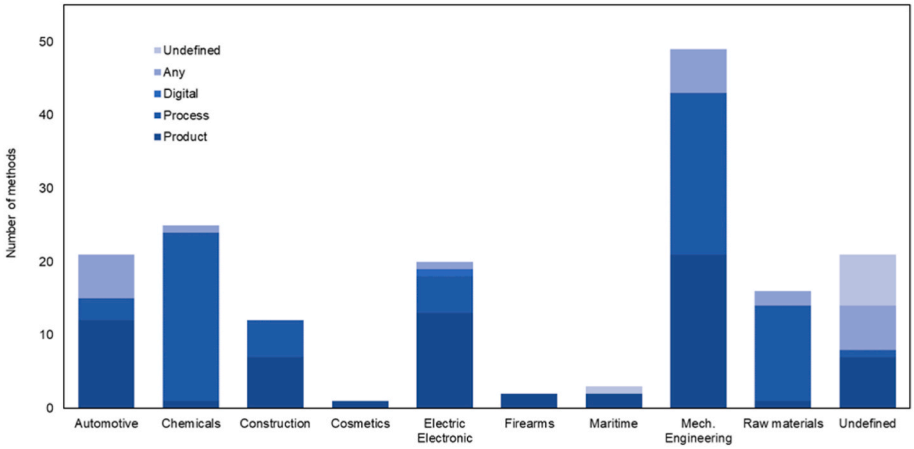

Fig. 2. Distribution of methods according to industrial sectors and types of technologies.

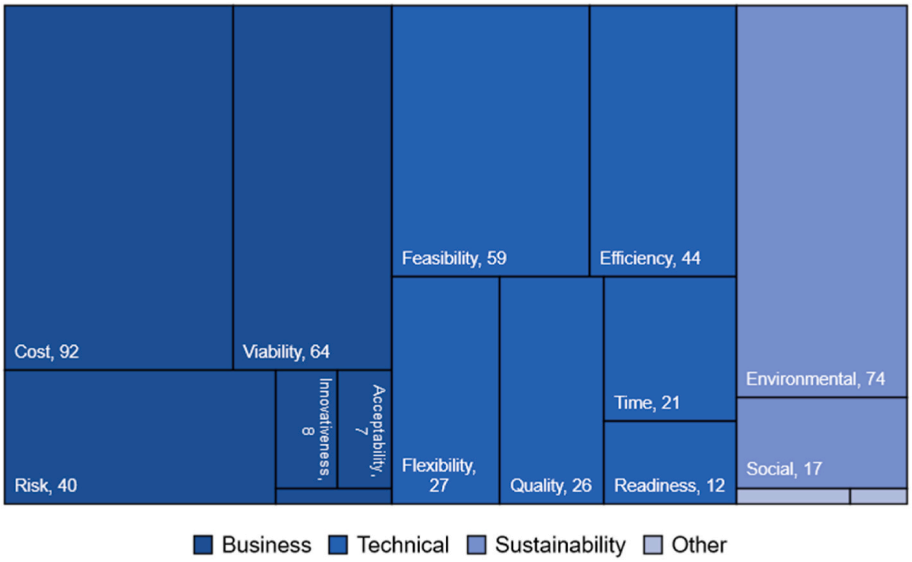

Fig. 3. The predominance of business and technical factors in the distribution of virtues considered by technology assessment methods. One method may consider multiple virtues.

= 92, labelled “Cost” in Fig. 3), viability (n = 64), and risk (n = 40), or technical figures, such as feasibility (n = 59), efficiency (n = 44), flexibility (n = 27), and quality (n = 26). Out of the methods that assess financial factors, most use direct cost measures (n = 57), while some calculate net present value (NPV, n = 12), return on investment (ROI, n = 7) or other metrics. Less than half of the methods included sustainability virtues, mostly environmental (n = 74) or social impacts (n = 17) of the adoption of a technology. Although several methods simultaneously assess financial and environmental factors (n = 54), only a minority (n = 19) explicitly considers trade-offs between them.

In addition to virtues, TA methods can also be analyzed according to the development stage they can be applied in and the type of data they require (Fig. 4). TA methods were described according to Cooper’s stages classification (Cooper, 2006), namely project scoping and technical assessment, detailed investigation, and business case. The methods were classified according to the *earliest* stage they could be applied to (i.e., a method categorized in “technical assessment” could also be applied to “detailed investigation”). Data requirements range from estimates (i.e., by experts in a workshop setting) to proxy data (extracted from similar or related technologies, such as a previous version or the currently used process), and finally real data (from experiments or simulations).

Findings show that most methods are applicable in scoping (i.e., portfolio management) and technical assessments, while few are relevant in business case stage. This is especially salient for sustainability-specific TA methods, which are inexistent in business case stage. Additionally, data requirements change significantly according to technology development stage. Results indicate that technology development is characterized by progressive data availability, as are other design and engineering activities (Shishank and Dekkers, 2013). More than half the methods aimed at later technology development stages require real data for the assessment (56% of business case stage methods), while in initial stages more than half of methods can operate with estimates (61% of project scoping or technical assessment methods).

In summary, the average TA method is focused on product innovation, measuring cost-related impacts, and is applied in the early scoping stages (i.e., portfolio management). The inclusion of sustainability concerns is not uncommon, but social impacts are rarely present. Finally, very few TA methods consider trade-offs between virtues, which can undermine their practical impact on decision-making.

3.2. *Clusters of technology assessment methods*

TA methods were clustered into 9 families (Fig. 5), according to their

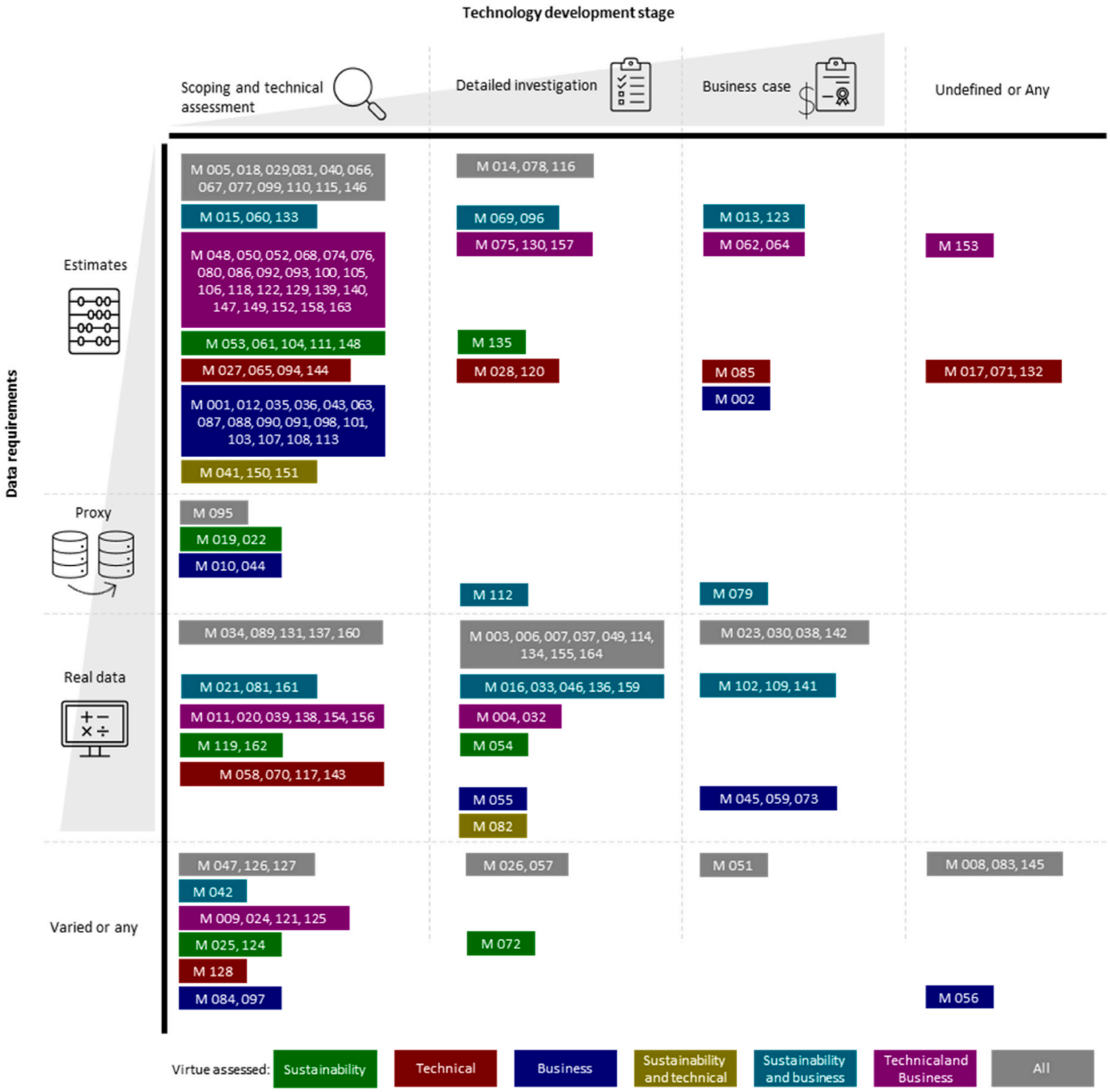

Fig. 4. Data requirements, technology development stage and virtues encompassed by technology assessment methods.

school of thought and main theoretical constructs. The classification considered the criteria used for the assessment (*prescribed* set of indicators versus *discretionary* choice) and degree of structure (the cluster is *structured* if the same steps or procedures are applied for all methods in it, while methods in *unstructured* clusters do not necessarily share the same guidelines). Although a clear-cut categorization was aimed for, the final clusters are arbitrary to an extent, and there is unavoidable overlap and connections between clusters. They are described and exemplified below. The examples shown do not represent an exhaustive list of all pertinent methods – refer to the supplementary material for the complete list of methods in each cluster.

- **Multi-criteria decision analysis (MCDA).** The most populated cluster, with 40 instances, combines all methods which employ primarily MCDA approaches to technology assessment. MCDA is an umbrella term for decision support methods where multiple criteria or factors are taken into account to select one alternative in a set of possibilities (Belton and Stewart, 2002). A plethora of MCMA methods have been employed to technology assessments, including analytical hierarchical process (AHP) [M146], outranking methods such as PROMETHEE [M018], TOPSIS, and others [M0154]. Many methods integrate fuzzy [M077] or grey numbers [M0122], with the goal of adapting the methods to qualitative data as well as incorporating some uncertainty management aspects. Methods from other clusters (e.g., FoM or LCA) can be used as inputs to MCDA methods.
- **Figures of Merit (FoM).** Also referred to as Key Performance Indicators (KPI), using indicators to assess key virtues of a technology is a well-understood and straightforward method. The 38 methods in this cluster comprise scorecards [M087] or two- or three-dimensional plots [M034] where technologies are rated using expert opinion [M030], estimates [M086] or actual data [M119]. Methods in this cluster do not present a clear recommendation of preferred technology alternative and decision to be made, setting them apart from the MCDA cluster. The most diverse cluster, methods in this category are used from the assessment of oil palm agriculture sustainability [M159] to capability manufacturing at NASA [M009].
- **Life Cycle-oriented (LCA/LCC).** The 35 methods in this category bring inspiration from Life Cycle Assessment (LCA) or Life Cycle Costing (LCC), prescribing a set of environmental or economic indicators for TA. LCA is the *de facto* standard method for product and process environmental impact assessment, with a large body of work

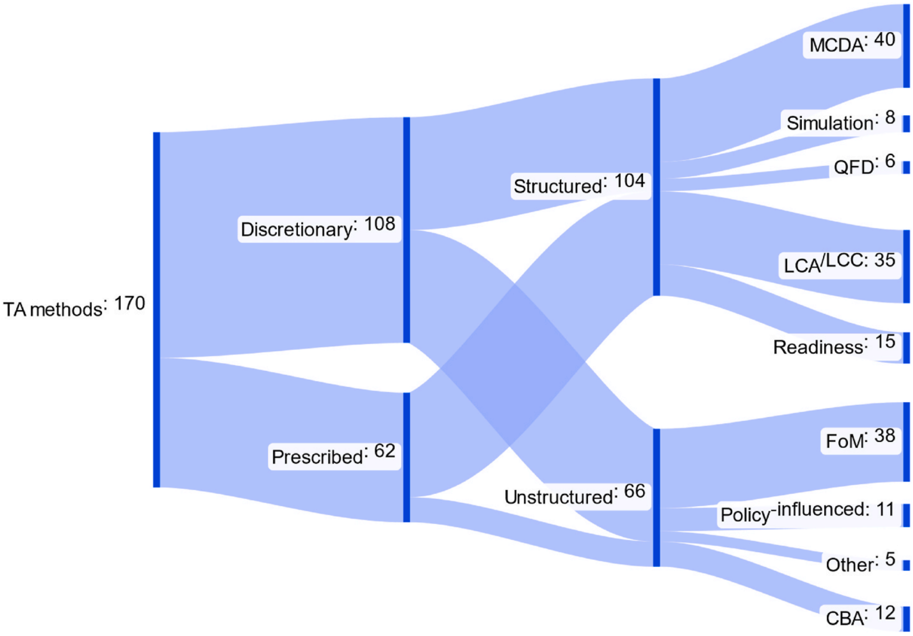

Fig. 5. TA method clusters. Methods were first categorized according to type of criteria used (*discretionary* choice of criteria or *prescribed*) and degree of structuredness.

concerning its application into early design activities, mainly product development (McAloone and Pigosso, 2018). While traditional LCA studies were excluded from the systematic review, methods in this cluster adapt the conventional steps of LCA to perform TA. Methods in this category include ex-ante [M022], prospective [M0123] and anticipatory [M053] LCA, where traditional LCA methodology is adapted for uncertain projects and emerging technologies. Additionally, there are several attempts at combining LCA with other features like techno-economic analysis [M008], uncertainty management [M141], cost-benefit analysis [M023], and multi-criteria decision analysis [M142].

- **Cost-benefit analysis (CBA).** Several assessment methods are used for feasibility and viability checks, usually considering potential monetary gains (benefits) and losses (often costs) of adopting a certain technology. This cluster with 12 methods includes purely financial analysis [M002], combinations of financial and technical evaluations [M012], and methods which combine financial, technical, and environmental evaluations [M049]. This cluster is seldom applied to low-maturity technology [M062], since financial performance data is rare in early design stages.
- **Readiness.** The 15 methods in this cluster have in common the aim of assessing the readiness or maturity of a technology. Most descend directly from the technology readiness levels (TRL) [M094], with eventual adaptations to include sustainability [M104], risk [M074], commercial potential [M071], and others. Methods in this category are flexible, being adaptable to several types of technologies in various stages of development.
- **Policy-inspired.** This category consists of methods influenced by the policymaking and policy-evaluation side of TA (Tran and Daim, 2008), such as participatory TA [M042], Delphi studies [M029], and advisory committees [M145]. The 11 methods in this cluster are always qualitative in nature and frequently applied to the very early stages of innovation and low-maturity technologies.
- **Simulation.** Methods in this category perform assessments by simulating the behavior of a technology and suggesting adaptations to optimize its performance. Three of the eight methods in this category are based on the Technology Identification, Evaluation, and Selection (TIES) tool used in the aerospace sector [M020] while others use custom equations for battery [M117] or energy technology [M131].
- **Quality function deployment (QFD).** This cluster of 6 methods includes variations on the QFD tool. These methods use QFD to identify or prioritize requirements for successful innovations and technologies. They range from “pure” QFD [M010], to combinations of QFD with Failure Modes and Effects Analysis (FMEA) [M140] and AHP [M138].
- **Other.** Five methods that did not fit in the previous categories, including risk-based assessments [M084] and FMEA-inspired tools [M133].

The assessment methods in clusters were classified according to their aim and type of measurement (Fig. 6). A method’s aim could be either: (i) the diagnosis of a technology, where aspects of the technology are explored and improvement opportunities are established; or (ii) finding the most appropriate alternative among a set of technologies or concepts. Type of measurement refers to the output of the assessment, which could be either an absolute result (i.e., “is this technology good or bad?“) or relative (i.e., “is this technology better or worse than another alternative?”). By placing the method clusters along these two dimensions, it is possible to visualize that most methods (LCA, MCDA, FoM, QFD, Policy-inspired, and Simulation) are commonly solution-focused where technologies are measured relatively. The readiness and CBA clusters, on the other hand, are often diagnosis-focused and assess technologies in absolute terms. Few methods present either solution-based assessment with absolute measurements or relative assessments for diagnosis purposes. The only cluster which is present in all four quadrants is FoM, although admittedly more prominent in the relative-solution section.

Most of the technology assessment methods employ some sort of technology forecasting (n = 83), although most use expert judgment to generate the forecasting (n = 56) to the detriment of more analytical methods (Mas-Machuca et al., 2014). Structured techniques to generate future scenarios are seldom applied (n = 27), usually relying on extrapolations from past data or expert judgment. Scenarios are primarily directed towards including uncertainty about external factors into the assessment.

Many methods that consider trade-offs between technology virtues

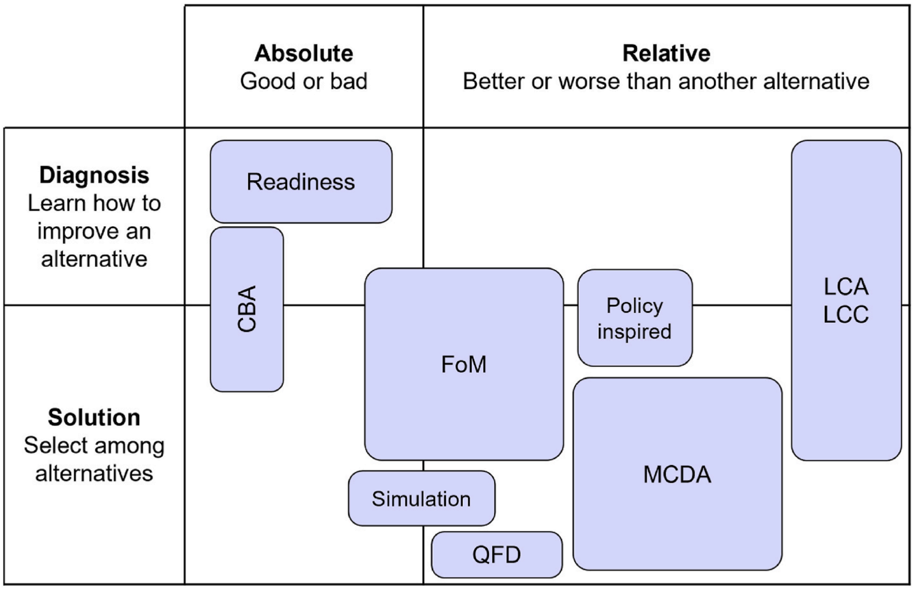

Fig. 6. Clusters of technology assessment methods according to aim and type of measurement. The area of each rectangle is proportional to the number of methods in each cluster.

do it explicitly (n = 85) by applying weights to indicators and combining them into a single composite index (n = 65). The remaining methods with design conflict considerations apply qualitative or visual approaches. Qualitative tools for trade-offs include checklists [M103], participatory methods [M042], and decision trees [M044]. Visualization techniques usually rely on direct comparison between two indicators or assessment dimensions [M007]. Most methods that refer to trade-offs, either implicitly or explicitly, fall into the MCDA (n = 39) or FoM (n = 34) clusters.

3.3. Sustainability in technology assessment

Sustainability is present in a large share of the methods (n = 78), and has become more common in recent years, as more than half the methods were published after 2018 (Fig. 7). SA methods for technology usually measure single or few environmental impacts, namely greenhouse gas emissions or, more broadly, climate change impacts. These methods rarely include environmental and social concerns at the same time, and very few exclusively assess social impacts (n = 2). On the other hand, combined assessment of environmental and economic impacts is common (n = 54), especially in methods that evaluate the contribution of a technology to the use-phase of an energy-consuming product. These methods often focus on energy saving, which may lead to both cost and environmental impact reduction, which can explain the simultaneous economic and environmental nature of the assessments.

No method mentions circular economy explicitly, although some include aspects of circularity, such as reducing the use of resources (24%). Circular Economy is a relatively recent concept in sustainability, defined as a “regenerative economic system” with the aim to promote “value maintenance and sustainable development” by “reducing, reusing, recycling, and recovering materials throughout the supply chain” (Kirchherr et al., 2023). Technology and innovation are widely considered to be enablers of this circular economic model (Guzzo et al., 2023). Very few methods in sustainability technology assessment encompass increasing lifetime of resources (4%) or closing the resource loop with recycling, reuse, and other end-of-life strategies (8%).

Technology sustainability assessment methods most commonly belong to the LCA or MCDA clusters, sometimes combining both approaches. Environmental concerns are especially common in methods designed for the chemical industry (32% of sustainability-related methods), which usually employ LCA-informed approaches. Sustainability-related methods frequently analyze either environmental impacts of production (30%) or use (33%) of a technology. Only 25% of sustainability-focused TA methods include impacts from cradle-to-grave, including sourcing and end-of-life.

Sustainability-focused assessment methods display some factors which may discourage their use in early-stage projects. They are mostly designed for higher technology maturity (only 12% aim at TRL <4) and later stages of the development process. Additionally, they are less tested in industrial cases (70% are not tested or evaluated in mock cases). Furthermore, they usually require intensive data collection which consequently makes application times longer (73% of tools take

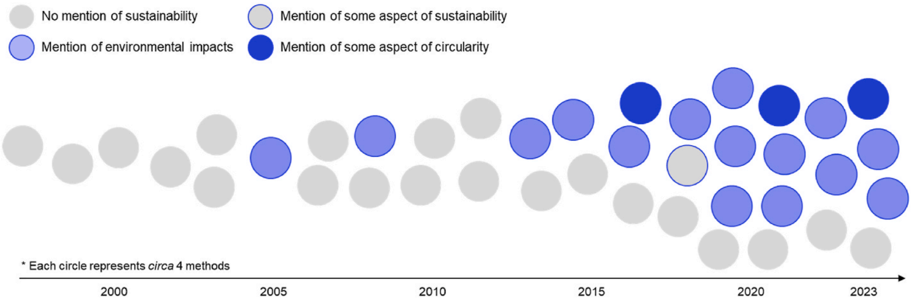

Fig. 7. Share of sustainability and circular economy related technology assessment methods included in the review. Each circle represents roughly 4 methods, according to year of publication.

Table 2

Initial design propositions (context and action) extracted from technology assessment methods. The strength rating indicates to what extent the action is more frequent in tested than untested methods. * = irrelevant strength or absence of action in sustainability-focused TA. TD = technology development.

Context	Actions from TA methods	Strength in general TA	Strength in sustainability-focused TA
Pre-conditions: before performing an assessment	DP01 Have a well-defined TD process	Moderate	Moderate
Planning: when designing and preparing TA	DP02 Design it for non-experts	Moderate	Low
	DP03 Involve the decision-maker	Moderate	Low
	DP04 Use workshop settings	High	Moderate
	DP05 Include diverse stakeholders	High	High
	DP06 Make it generic	High	*
Evaluation: when appraising technologies	DP07 Use leading indicators	Low	Moderate
	DP08 Use multiple indicators	High	High
	DP09 Use qualitative indicators	Low	Moderate
	DP10 Use simple scoring methods	Moderate	High
	DP11 Use real data if possible	High	High
Interpretation: when analysing the results of TA	DP12 Consider the trade-offs	Moderate	*
	DP13 Consider the uncertainty	Moderate	*
	DP14 Consider future scenarios	Moderate	Low

more than one person-day to perform).

4. Design propositions

To understand how to improve sustainability assessment methods for early-stage innovation projects, we extracted initial design propositions (DP) from tested technology assessment methods (Fig. 1). The design propositions shown in Table 2 can be interpreted as a list of recommended actions for technology assessment in certain contexts. The contexts refer to various stages in a TA implementation, namely organizational *pre-conditions* (before performing an assessment), *planning* (when designing and preparing an assessment), *evaluation* (when appraising technologies), and *interpretation* (when analyzing the results). Each action is followed by a strength rating, which represents to what extent the action is more frequent in tested than untested methods, that is, the action's importance. A high strength denotes that tested methods include the action exceedingly more (15% or more) than untested ones. On the other hand, a low strength implies that the action is only slightly more common (between 5 and 10%) in tested than untested methods.

Furthermore, the extent to which the design propositions extracted from TA methods are also adopted by sustainability-focused methods was evaluated. This allowed the identification of commonalities and differences of best practices between sustainability-focused methods and TA methods not driven by sustainability. To do this, the procedure to obtain TA best practices was repeated exclusively with sustainability methods. That is, a certain characteristic was said to be a best practice if its occurrence was significantly higher in tested than untested sustainability-oriented TA methods, and the difference in occurrence is shown as the strength rating in the rightmost column of Table 2. Design propositions may be well adopted by sustainability-focused methods, in which the strength rating is equal or higher in sustainability-focused TA than in general TA. Another possibility may be that the action is frequently adopted in sustainability methods but slightly less common than in general TA methods. In more extreme cases, actions from TA methods are absent from sustainability methods (marked by *).

Each design principle is detailed in the following subsections, grouped by context. Possible mechanisms and outcomes for these actions are further explored in section 5, completing the traditional CAMO format of design propositions (Romme and Dimov, 2021).

4.1. Context: pre-conditions

One organizational pre-condition for effective TA application was identified and described below.

DP01: Having a well-defined technology development process is preferred to having no structure to the front-end of innovation process. A TA tool must be aligned to the process where it is employed, be it a technology stage-gate model (Cooper, 2006) or more iterative approaches (Aristodemou et al., 2019). This is not always straightforward, as even stage-gate models for technology development may retain certain "fuzzy" characteristics of innovation processes, such as not having clear requirements at development gates or a pre-defined number of stages (Ajamian and Koen, 2002). For example, one scorecard method for innovation [M087] implements this design proposition by aligning assessment activities in gate-meetings at the end of each development stage. The assessment activities include appraisals of cost and success potential, calculated by scoring the technology according to competitiveness, market size, competitor intensity, etc. This action is also observed to the same extent in tested sustainability-related methods. The ETEA framework tool [M026], for example, follows a stage-gate approach based on TRL for green technologies – the activities suggested by the framework are applied at each development gate and change according to the maturity of the technology.

4.2. Context: planning

When preparing for a technology assessment exercise or designing a tool to support the assessment, five design propositions have been identified and are discussed below.

DP02: Designing the assessment tool for non-expert users is moderately more common in tested TA methods. "Non-expert" refers to users without expertise in either the assessment method or the virtue being evaluated. For example, in the case of cost-benefit analysis, a non-expert user would not be highly familiar with financial metrics or the methodology itself. Methods following this design proposition usually fall outside the LCA or MCDA clusters. An example would be MEPT [M050] method development by Siemens in which an easy-to-understand scorecard is used to judge the attractiveness and technological position of a company's portfolio. The appraisals in MEPT are established via expert scoring of factors such as development potential, customer acceptance, and availability of human and financial resources. In sustainability-related tools, this action is present to a lesser extent. This could be due to the high influence of LCA and other product development approaches to sustainability quantification, which usually require more expert knowledge to be applied (McAloone and Pigosso, 2018). The design proposition is applied in the IISA method [M111], for example, which uses open public events to crowd-evaluate social aspects of innovations and map stakeholders' acceptance of the technology.

DP03: Involving the decision-maker during the assessment, and not only in the interpretation stage, is a best practice in TA methods. This design proposition can be exemplified by the STAR method [M152], in which technologies are assessed following a real-options approach. The appraisal is performed in project group which includes the project leader or other decision-makers. Through a checklist containing questions about strategic and financial aspects of the technology, the project group reaches a single conclusion, in consensus, and the decision is made collectively. The checklist contains statements such as “the technology will be able to offer substantial performance advantages over current solutions” and “we have the right skills in place for commercialization.” This design proposition is less occurring in sustainability-focused projects. This could be explained by the common view that sustainability assessment requires people in specialist roles, which are often not decision-makers. One pairwise comparison tool [M030] employs this proposition by developing personas to reflect the views of decision-makers from distinct parts of the organization. Each persona is then used to develop weights for the evaluation criteria. For instance, a persona representing an environmental enthusiast would rate the “carbon intensity” of the technology as very important, while “ease of delivery” would receive a relatively low importance. On the flipside, a persona representing a local resident of the area where the technology would be deployed would have inverted these importance ratings.

DP04: Implementing assessment tools in workshop settings with facilitation is recommended as opposed to software or spreadsheets for individual use. Workshop settings can be employed for group assessment of technologies with physical (i.e., paper-based) methods or digital approaches. The future oriented risk assessment method [M084] proposes participative approaches such as workshops and brainstorms to align technology assessment with risk assessment, displaying the use of the design proposition. Although less common in sustainability-related tools, there are methods which employ facilitation for environmental impact assessment such as Pindar [M048], used for robotics design. In Pindar, a series of facilitated evaluation steps are executed, from the selection of evaluation criteria to the quantification of results, guiding the choice of the most promising robotics design proposals.

DP05: Including a diverse set of stakeholders is preferred to relying solely on the development project personnel to assess technologies. Stakeholders included could be internal to the company, but in different departments, exemplified by the BRLa framework for emerging technologies [M017], or external, such as final users of the technology, shown in the SCORE method for defense and military applications [M011]. In BRLa, or Balanced Readiness Level assessment, different “readiness” aspects of technologies are evaluated by a broad group of experts from within the company. The assessments include technology readiness levels, market readiness levels, organizational readiness levels, etc. In SCORE, feedback from actual end-users is captures in testing settings and is then incorporated into the technology assessment. The design proposition is also highly relevant in sustainability assessment tools, as employed in the LCA-inspired study of a bus fleet in Qatar [M161] which considered different user groups in its analysis.

DP06: Designing the assessment tool to be generic is substantially more common in tested TA methods than untested ones. Generic tools are easy to understand and to apply to a broad range of industries. A generic and wide-ranging tool such as the innovation impact map [M113] can be used to evaluate the opportunities provided by distinct types of technologies in many industries, improving its uptake by manufacturing companies. The innovation impact map proposes a quantification of quality-of-life improvements as a consequence of the adoption of a technology, and it is not limited to a specific type of technology of industry. However, the design proposition extracted from sustainability-focused assessment methods points at the opposite direction – tested tools tend to be more specific than untested ones. Possible explanations for this conflict are explored in section 5.2. A generic SA method for technology can be exemplified by [M136], a multi-indicator assessment method comprised of guidelines for economic, environmental, and social indicators selection and application. This method, although developed for sorting technologies of e-waste, can also be used to guide indicator selection for other types of process technologies. Specific tools for sustainability can be illustrated by the guidelines on how to conduct LCA combined with techno-economic assessment for specific carbon capture and utilization technologies [M142].

4.3. Context: evaluation

When executing the appraisal of a technology, five design propositions have been identified, as described below. All actions in this context are present to the same extent in both general TA and sustainability-focused ones.

DP07: Using leading indicators in place of lagging indicators. Lagging indicators reflect final outcomes, while leading indicators monitor the current situation (Pojasek, 2009). The use of leading indicators is exemplified in tools like the Combined Compromise Solution (CoCoSo) [M004], used to select manufacturing technologies with a MCDA approach, or the sustainability-driven [M060] where expert judgement is used to rate product related technological scenarios using pre-defined leading indicators. In CoCoSo, a set of indicators (such as quality, cost, and profit from after sale services) are combined using a series of mathematical expressions and matrices and used to appraise a novel technology. In [M060], leading indicators are chosen to represent the triple bottom-line of sustainability: economic, environmental, and social aspects. Results are then displayed in radar plots.

DP08: Employing multiple indicators instead of a single metric. Multiple indicators can better capture the nuances of a technology assessment problem when they are not weighted or in any way combined into a single (composite) measure. For example, they are present in US Air Force’s QTA method [M028], an analytic method to capture the impact of new technologies on aircraft performance. Several indicators of a technology’s impact on aircraft performance are considered simultaneously, such as fuel flow, drag, and weight. In sustainability-focused methods, we can observe multiple indicators being employed in a visualization technique for sustainable energy system scenarios [M131]. The technique combines indicators for measuring energy generation, energy consumption, and greenhouse gas emissions for each developed scenario.

DP09: Applying qualitative indicators rather than quantitative ones. Methods applying this design proposition usually fall outside the LCA and MCDA clusters. Qualitative data can be easier to obtain than quantitative information, especially in early stages of technology development. Qualitative data used for technology assessment can range from interviews for ethical evaluation [M061] (e.g., “does the technology enhance or diminish your sense of control?“) to Likert-scale questionnaire about innovation used in the MIM method [M110] (including questions about protection level, global technical environment, and competitor’s competence). In MIM, the degree of innovation of a technology is measured in a scale that goes from “there is a sophisticated product and a huge identified market” to “preliminary idea for a product, the market is not well defined.”

DP10: Using simple matrix or scoring methods, instead of algorithms, simulations, and other software tools. Matrix and scoring methods consist of a series of indicators, usually organized in tabular form, which are either scored following a pre-defined scale or filled in with available data. This approach tends to be easier to understand and implement when compared to more sophisticated algorithms or software. Technology assessment methods employing this design principle can be illustrated by QFD approaches ([M138] combines QFD and AHP for augmented reality technology selection, where QFD is used to identify relevant criteria and AHP is used to rank criteria against each other), MCDA methods (MAUT [M137] uses utility theory to formally map preferences of the decision makers and important scoring criteria), or several KPI tools (US EPA’s GREENSCOPE [M037] consisting of environmental and economic indicators arranged visually for characterization of chemical process technologies, such as ethanol manufacturing from biomass).

DP11: Using real data, if possible, rather than estimates or proxy information. This design principle is more common in higher maturity technology, where experimental or pilot-scale data may already be available. For example, TCM [M073] uses a computer-based spreadsheet technique to simulate manufacturing costs based on historical data and data regressions. TCM has been used to identify cost drivers and economic potential in production technologies of ceramic matrix composites, diamond films, engine components, among others. In the sustainability-based methods, the ones in the LCA cluster often require real data, like in the highly specific method [M006] combining LCA and AHP for technologies in the coal industry.

4.4. Context: interpretation

Finally, when interpreting the results from technology assessment, three design propositions have been extracted and are discussed in this subsection.

DP12: Considering the trade-offs and conflicts between technology virtues is more common in tested methods than in the untested ones. Trade-offs are situations in (product or technology) design where all existing requirements cannot be simultaneously satisfied by the current alternative (Andreasen et al., 2015). To deal with these conflicts, the assessment must consider how improving one virtue may (negatively) affect another. For example, TOPSIS and CBA can be combined to simultaneously evaluate several virtues of semiconductors manufacturing processes, as suggested by [M154]. In this method, benefits for company managers are defined as important technology attributes, such as production lead time, flexibility, and quality. The relative importance of the attributes, alongside technology implementation cost, are ranked by the same managers, providing key information to solve trade-offs. Finally, the technology alternatives are ranked using this preference information via the TOPSIS method. However, for sustainability assessment methods, this design proposition does not hold (i.e., consideration of trade-offs occurs equally in tested and untested tools). Possible reasons for this discrepancy between generic TA and sustainability-focused methods are further discussed in section 5.2. An example where trade-offs between environmental issues and other virtues are considered is the QSA method [M033], which combines LCA and economic analysis and simulation in the chemical industry. The results of both assessments are taken into account simultaneously whenever a technology development decision is made.

DP13: Considering the uncertainty in data and context. Technology development and other early innovation activities are often stated to be “fuzzy” (Eling and Herstatt, 2017), largely due to the several types of uncertainty that occur in the front-end of innovation and that may hinder technology assessments. Data uncertainty, commonly associated with early design activities (Andreasen et al., 2015), can limit the types of assessment methods that may be applied. More troublesome are context uncertainties, such as those related to technical factors, organizational factors, markets, and resources, which are particular to innovation activities (O’Connor and Rice, 2013). Most methods which proposed to deal with uncertainties left out the influence of these contextual factors. There are multiple ways to manage uncertainties in technology assessment, ranging from mostly qualitative to mostly quantitative methods. A proposed NASA lunar outpost program [M044] used decision trees and sensitivity analysis for decision support. The method model different system characteristics and analyses their impacts at a system level. A “hard” approach is taken by [M077], which includes a fuzzy best-worst method for new product idea selection under group decision-making, with rigorous quantification of uncertainty. In sustainability-focused methods, this design proposition is mostly absent in the studied tools. The possible reasons behind this are further discussed in section 5.2.

DP14: Considering future scenarios in structured ways are preferred to ad-hoc approaches or not using foresight techniques at all. Foresight methods can be useful in technology assessment tools to reduce (context) uncertainties and lead to more informed decisions (Keenan et al., 2007). For example, scenarios can be created in a systematic way to address the impact of market-related factors to financial aspects of a technology [M120]. Scenarios in this method are used as a sort of sensitivity analysis and robustness check to verify if technologies would maintain their placement in the assessment even in non-ideal future situations. This design proposition is less common in sustainability assessment methods, which usually use unstructured approaches to technology foresight, if at all. A contrasting example [M042] uses a participative method to co-develop scenarios from narratives and visions that participants have regarding the promises of additive manufacturing. As the authors of the method state, “the goal is to move from often little reflected *technology-driven visions* to reflexive *socio-technical scenarios* that address the complexity of grand challenges in a more relevant way.”

5. Discussion

In this section the learnings from technology assessment best practices that could support the design and effective implementation of sustainability assessment are discussed. First, possible mechanisms to explain the design propositions established in section 4 are explored, elucidating how these actions may lead to positive outcomes in TA. Finally, the gaps between sustainability-focused and non-sustainability-focused TA methods are investigated, resulting in an analysis of how the design propositions may be applied to early-stage SA tools.

5.1. Mechanisms and outcomes of design propositions

A complete design proposition must establish the generative mechanisms and expected outcomes of an action in a given context (Romme and Dimov, 2021). The mechanisms aim to explain why a certain action works to achieve a certain outcome. In this research, the possible mechanisms and outcomes of the design propositions were investigated using abductive thinking and are discussed in the remainder of this section (Tables 3–5). The mechanisms should be interpreted as initial

Table 3
Mechanisms for the design propositions before technology assessment and when designing and preparing (pre-condition and planning context). TD = technology development.

Design proposition	Action (A)	Proposed outcome (O)	Proposed mechanism (M)
DP01	Have a well-defined TD process	to increase adoption of the assessment tool	since companies with a greater level of formalization are better equipped to implement management tools (Nijssen and Frambach, 2000)
DP02	Design it for non-experts	to increase adoption of the assessment tool	by making its structure and process user-friendly and accessible (Kerr et al., 2013)
DP03	Involve the decision-maker	(i) to increase adoption of the assessment tool or (ii) to enhance decision-making reliability	(i) by driving accountability of top management (Nijssen and Frambach, 2000) or (ii) by increasing acceptance of results (Wiebe et al., 2018)
DP04	Use workshop settings	to enhance decision-making reliability	by increasing levels of communication and knowledge-sharing among participants (Franco and Montibeller, 2010)
DP05	Include diverse stakeholders	to enhance decision-making reliability	by allowing individuals to engage with one another and co-create solutions (Kerr et al., 2013)
DP06	Make it generic	to increase adoption of the assessment tool	by increasing user-friendliness (Kerr et al., 2013)

Table 4
Mechanisms for design propositions when appraising technologies (evaluation context).

Design proposition	Action (A)	Proposed outcome (O)	Proposed mechanism (M)
DP07	Use leading indicators	to promote early and preventive action	by monitoring the degree to which best practices are being followed (Pojasek, 2009)
DP08	Use multiple indicators	to represent a more complete picture of the technology	by including a broader set of issues and sub-components of a complex system (Greco et al., 2019; Mitchell et al., 2022)
DP09	Use qualitative indicators	to increase adoption of the assessment tool	by facilitating communication and engagement of participants (Franco and Montibeller, 2010)
DP10	Use scoring methods	to achieve a robust yet easy assessment	by breaking down a complex assignment into simple evaluations (Kerr et al., 2013; Mitchell et al., 2022)
DP11	Use real data	to enhance decision-making reliability	by basing results upon a sound knowledge base (Keenan et al., 2007)

Table 5
Mechanisms and actions for the design propositions when analyzing technology assessment results (interpretation context).

Design proposition	Action (A)	Proposed outcome (O)	Proposed mechanism (M)
DP12	Consider the trade-offs	to make better decisions	by reflecting on possible conflicting impacts of a technology (Belton and Stewart, 2002)
DP13	Consider the uncertainty	to ensure more trustworthy results	since technology development projects are fuzzy and it is important to understand the range of possible outcomes (Mitchell et al., 2022)
DP14	Consider future scenarios	to enhance decision-making	by increasing the awareness of decision context and criteria (Chermack, 2004; Parolin et al., 2023)

proposals containing possible explanations for the design propositions and reflect a limited body of knowledge in the literature within technology and innovation management, futures studies, and engineering design.

In the pre-conditions and planning context (Table 3), literature points at two positive outcomes that may be achieved through different mechanisms: (i) a higher adoption of the tool in the organization; and (ii) increased reliability and trustworthiness of decisions. Regarding driving up the adoption of TA tools, companies working with a higher level of formalization in product development process are shown to be better equipped to implement management tools (Nijssen and Frambach, 2000). This mechanism, if transposed to technology development, may explain why TA tools designed for a well-defined process (DP01) achieve higher adoption rates. Tools in compliance with DP01 are easier to set up in an organization with structured technology development processes and are less dependent on the willingness of specific people in the organization to be effectively used. On the other hand, if the company does not have an established process for technology development, this may constrain which tools can be employed and subdue the positive effect of the applied tools. Similarly, technology management toolkits with user-friendly processes and modular or generic structure show increased adoption rates (Kerr et al., 2013). This effect may clarify why designing simple and generic tools (DP06) for non-expert users (DP02) are best practices for TA methods. Another way to achieve higher adoption of assessment tools is by driving accountability and participation of top management, which is shown to play a key role in the success of new product development (Nijssen and Frambach, 2000). If this mechanism can be transported to technology development, it may explain why having the direct involvement of decision-makers in the evaluation process (DP03) can lead to positive outcomes.

Additionally, actions in the preparation context can also lead to more robust decisions. The involvement of the decision-maker in the assessment (DP03) can increase acceptance of results by others (Wiebe et al., 2018) and enhance the legitimacy of the decision. It may also streamline the assessment procedure, as the decision-maker, by participating directly, becomes aware of assumptions and limitations of the analysis earlier on in the process. However, when decision-makers are involved, their hierarchical position can cause other participants to feel overruled and afraid to speak up, possibly resulting in sub-optimal decisions (Kerr and Tindale, 2004). Furthermore, the inclusion of a group of decision-makers in the evaluation may be challenging for practical reasons (e.g., space limitations, logistic or scheduling constraints).

Technology management scholars argue that workshop settings (DP04) generate more trustworthy decisions, as they increase levels of communication and knowledge-sharing among participants (Franco and Montibeller, 2010). The same is said of including diverse participants (DP05) in the assessment (Kerr et al., 2013), which are then incentivized to reach consensus and co-create solutions, driving increased reliability and trustworthiness of the decision. On the negative side, large assessments including multiple stakeholders can be drawn out and delay the decision-making process (Wiebe et al., 2018).

There is abundant literature on the potential benefits of using multiple qualitative leading indicators in management tools, in the context of evaluating technologies (Table 4). Leading indicators (DP07) are argued to have positive effects in promoting early and preventive action (Pojasek, 2009), by offering a way to monitor the degree of compliance with management criteria instead of measuring outcomes. Multiple indicators (DP08) can be used to map a more complete picture of the impacts of a technology by including in the assessment a broader set of issues and sub-components of a complex system (Greco et al., 2019). Qualitative indicators (DP09) are shown to increase adoption of the assessment tool by simplifying the assessment (Franco and Montibeller, 2010) and better representing the participants think and communicate in the early-design stages. Simplification is also argued to be the main mechanism behind the use of scoring methods (DP10) (Mitchell et al., 2022), as they offer a robust yet easy method to breakdown complex assignments into simple evaluations (Kerr et al., 2013).

On the other hand, the use of purely qualitative indicators can be challenging in a highly technical setting which is part of an engineering organization, such as technology development. Decision-makers and participants may prefer quantitative indicators in an aggregated form, which are more readily understandable (Greco et al., 2019). Additionally, the use of scorecard methods may increase the likelihood of participants distrusting the assessment if the scoring is too vague, inconsistent, or not representative of their values. These concerns can be alleviated using real data (DP11) to substantiate the assessment, which is reasoned to increase the trustworthiness of decision-making, by ensuring results are “based upon a sound knowledge base” (Keenan et al., 2007). Combining qualitative indicators and real data requirements is a delicate balance between simplicity and reliability.

In the interpretation context (Table 5), actions are argued to contribute to more informed and robust decisions. Considering trade-offs between options (DP12) may help uncover hidden costs or benefits of different alternatives and compare them on a common basis (Belton and Stewart, 2002; Kravchenko et al., 2020a). Being transparent about uncertainty (DP13) can also lead to more credible results by ensuring that limitations and assumptions regarding data and context are acknowledged in the assessment (Mitchell et al., 2022). Finally, the use of foresight techniques such as future scenarios (DP14) may result in more comprehensive decisions by allowing the exploration of possible changes to the decision context and increasing awareness of uncertainties in the assessment (Chermack, 2004).

5.2. Gaps in sustainability assessment methods

The dominant position in sustainable design literature sometimes does not align with the design propositions – possible reasons for these gaps are explored in this section. The design propositions for general technology assessment methods were analyzed in the context of sustainable design literature (Table 6). The investigated sustainability-related literature is focused on studies of sustainability assessment methods and tools, and it is not limited to technology development but includes also new product development, innovation topics more broadly, and SA as applied in other disciplines.

Best practices extracted from sustainability-related literature match most of the design propositions in the preparation context, with the noted exception of a discussion around generalizability versus customization of assessment tools. In his PhD thesis (O'Hare, 2010), O'Hare presents recommendations of eco-innovation tools for the early design stages, backed by industrial investigation and literature reviews. The author states that environmental considerations should be integrated within the new product development process, matching the first proposed action in this study (DP01) (Pigosso et al., 2014). Additionally, O'Hare incentivizes the use of tools that require a low level of effort to be applied and that are "easy to learn, understand and use," especially in early design stages, mirroring DP02. However, the author also states that one should "customize the tools to the specific company or application" (O'Hare, 2010), which may conflict with DP06. In fact, SA tools for technologies tend to be specific to a certain use-case, as evidenced in Table 2. We can hypothesize that the lack of generic tools for sustainability assessment may come from the (apparent) need for more specialist knowledge when evaluating environmental and social impacts, compared to business-related metrics. Sustainability assessment tend to be complex methods (Huang, 2021) that may require more tailoring for company-specific characteristics to make it useable by non-sustainability experts (McAloone and Pigosso, 2018).

The other actions in the preparation context are largely supported by sustainable design literature. Participation of decision-makers in collaborative TA exercises (DP03) has been shown to have positive effects (Gasde et al., 2020a) in the decision. Workshop settings (DP04) were shown to increase participants' "consideration of technology value towards customers, society as a whole and the environment" (Farrukh and Holgado, 2020). However, awareness may not be enough and such workshop activities may need to be qualified and complemented by more analytical approaches. The importance of stakeholder engagement (DP06) was argued for in front-end of innovation activities, like sustainable business model innovation (Pieroni et al., 2018; Schlüter et al., 2023), and in other types of technology assessment, namely in policy making and evaluation (Sala et al., 2015).

The design propositions in the evaluation context are moderately endorsed in sustainable design literature. The use of leading indicators (DP07) is commonly advocated for: (i) measuring corporate circular economy initiatives (Kravchenko et al., 2020b); (ii) evaluating product-related environmental performance (Issa et al., 2015); and (iii) gauging process-related environmental performance (Rodrigues et al., 2016, 2017). Likewise, scorecard methods (DP10) find applications in SA deployed in technology development (Farrukh and Holgado, 2020) and new product development (McAloone and Bey, 2009).

On the other hand, having multiple indicators (DP08) is less represented as a best practice in sustainability literature. It is seen as a positive feature of SA (Sala et al., 2015), but there are claims that multiple indicators can make decision-making more complicated, since there may be conflicts between indicators (Saidani et al., 2021). While it is understandable that presenting multiple indicators may result in a less

Table 6
Relationship and alignment (agreement) between design propositions and sustainability assessment literature. TD = technology development.

Design proposition	Action	Recommendation from sustainability assessment literature	Alignment
DP01	Have a well-defined TD process	Environmental considerations should be integrated within the development process (O'Hare, 2010)	++
DP02	Design it for non-experts	Tools should require little effort and be "easy to learn, understand and use," especially in early design stages (O'Hare, 2010)	++
DP03	Involve the decision-maker	Participation of decision-makers in collaborative assessments has been shown to have positive effects (Gasde et al., 2020a)	++
DP04	Use workshop settings	Workshop settings were shown to increase participants' awareness of the impacts of a technology (Farrukh and Holgado, 2020)	++
DP05	Include diverse stakeholders	The importance of diverse stakeholder engagement was shown in other sustainability-related activities (Sala et al., 2015; Schlüter et al., 2023)	++
DP06	Make it generic	SA literature points at the opposite direction, as in tools should be company-specific (O'Hare, 2010)	o
DP07	Use leading indicators	Leading indicators are recommended for early design stages and several sustainability-related corporate activities (Issa et al., 2015; Kravchenko et al., 2020b; Rodrigues et al., 2016)	++
DP08	Use multiple indicators	While having multiple indicators is sometimes recognized as a positive feature in SA, there are doubts about its efficacy (Saidani et al., 2021)	+
DP09	Use qualitative indicators	Early-stage SA often resorts to qualitative indicators in the case of lack of data (Chebaeva et al., 2021; Kravchenko et al., 2020a), but later-stage SA is more quantitative	+
DP10	Use scoring methods	Scorecards for SA are ordinary in product development (Farrukh and Holgado, 2020; McAloone and Bey, 2009), and may also be applicable to technology development.	++
DP11	Use real data whenever possible	Early-stage SA tends to use estimates in detriment of real data, due to resource availability issues (N. Matthews et al., 2019a)	o
DP12	Consider the trade-offs	Dealing with trade-offs is a major challenge of SA (Dekoninck et al., 2016; Schlüter et al., 2023)	++
DP13	Consider the uncertainty	Uncertainty quantification and management are key research areas within SA (Sala et al., 2015)	++
DP14	Consider future scenarios	Scenarios and other foresight methods are increasingly valued in SA methods (Bisinella et al., 2021)	++

straightforward conclusion, clearly displaying conflicts between sustainability aspects can be a positive consequence for SA, helping uncover uncertainties and capturing a broader view of sustainability. Similarly debatable is the use of qualitative indicators (DP09). Early-stage SA often resorts to qualitative indicators (DP09) in the case of lack of data, as seen in R&D projects assessment (Chebaeva et al., 2021) and product development projects (Kravchenko et al., 2020a), whereas later-stage SA is traditionally carried out in quantitative terms using specialized software, the case of LCA (McAloone and Pigosso, 2018). Also not supported by sustainable design literature is the use of real data (DP11), since early-stage SA typically asks for the use of estimates or proxy measures due to resource availability issues (Matthews et al., 2019a,b). A combination of real data and estimates may be an adequate compromise to ensure ease of use and trustworthiness of the assessment.

Sustainable design literature generally supports research and implementation of the design propositions in the interpretation context. How to deal with trade-offs (DP12) is a major challenge of sustainability evaluation in product development and innovation (Dekoninck et al., 2016; Schlüter et al., 2023) and several methods have been proposed recently, from manufacturing companies (Kravchenko et al., 2020a) to the built environment (de Magalhães et al., 2019). The same can be said about uncertainty quantification and management (DP13), which is recognized as a key research area within SA (Sala et al., 2015). Scenarios (DP14) and foresight techniques are also increasingly valued ways of incorporating uncertainty into sustainability assessment (Bisinella et al., 2021).

In contrast, the design propositions in the interpretation context are rarely employed in practice (Table 2), even as they are valued by sustainable design scholars. A plausible reason for this lack of adherence to best practices could be the increased methodological sophistication needed from SA tools to employ these actions. Similarly, conducting uncertainty and trade-off management could be a time-consuming and resource-intensive task, which may not fit within the technology development constraints. Finally, these practices may challenge existing norms and expectations of decision-makers (Sala et al., 2015), leading to "fuzzier" decisions and less deterministic results.

5.3. Developing and adapting sustainability-focused methods for technology assessment

In addition to the design propositions themselves, there are several opportunities to improve tools aimed at assessing the sustainability of new technologies in manufacturing companies, according to the gaps discussed throughout this study. Specifically, the following remarks stem from: (i) the gaps in sustainability-focused technology assessment methods (section 3.2); (ii) the differences between design propositions extracted from generic TA methods and sustainability-oriented ones (Table 2); and (iii) the disagreements that exist when it comes to linking TA best practices and SA literature explored (section 5.2).

- Some recognized best practices in both TA and SA are still not largely employed in SA methods for technology development, such as uncertainty and trade-off management. The use of simplified approaches to uncertainty quantification and streamlined MCDA methods which do not require extensive calculations are possible "low hanging fruit" actions to improve existing sustainability-focused TA tools.
- There needs to be a reconciliation between the advantages of generic TA methods (broad applicability and apparent simplicity) and the perceived benefits of company-specific SA tools (efficiency and ease of use). Kerr et al. suggest one possible solution (Kerr et al., 2013) which recommend the development of flexible and modular tools, consisting of a general form that can be made specific according to the needs of a company or industry.
- Furthermore, methods which include circularity criteria into the assessment are inexistent in the studies included in this review. At the same time, initiatives to include circular economy principles into companies' practices, including technology and product design, are increasingly common, but are seldom evaluated according to their environmental or social impacts (Das et al., 2022). As a first step to fill this evaluation gap in technology development, current TA methods based on leading indicators could be adapted to include circularity-related figures from existing databases (Kravchenko et al., 2020b).
- Finally, although process models for technology development exist for decades (Aristodemou et al., 2019), there are few SA tools for technology which are clearly designed with process integration in mind. Other organizational barriers to the implementation of appropriate tools must also be investigated, including which competences and resources are needed in the front end of innovation to enable the use of these methods, but also the role of culture and leadership (Dekoninck et al., 2016).

There are some existing sustainability-focused technology assessment tools included in this study, which fulfil the design propositions and the recommendations above to a considerable extent. A notable example is method M115 (Farrukh and Holgado, 2020), a modular toolset for early-stage TA including scoring sustainability criteria. Implemented in a facilitated setting and tested in industrial workshops, it was shown to lead to useful discussions among the project group members. The method includes value mapping and stakeholder identification exercises. Lacking from the method is the explicit consideration for trade-offs and future scenarios, although both aspects are, to a certain extent, covered implicitly. Additionally, circularity aspects are not mentioned and there is no predefined set of indicators or sustainability criteria recommended to users. Making use of the modular aspect of this tool, the aforementioned functionalities or characteristics could be included in the method as new modules on top of the existing elements.

6. Conclusion

In this paper, TA methods for manufacturing companies are systematically catalogued and explored in relation to SA. The importance of the front-end of innovation and technology development in manufacturing companies was explored, as was the need to integrate sustainability considerations into these activities. In total, 170 existing TA methods were mapped and categorized through a systematic literature review, identifying their strengths and limitations. From this collection of TA methods, a set of design propositions or best practices for technology assessment was proposed. Using a design science approach, the potential for technology assessment methods to be expanded to include sustainability considerations was demonstrated, highlighting the importance of doing so considering increasing pressure for companies to address their environmental and social impacts. By integrating sustainability into state-of-the-art TA methods, manufacturing companies can improve their innovation processes, increase the value of their offerings, and contribute to a more sustainable future.

Our findings have practical implications for manufacturing companies seeking to improve the sustainability performance of their technologies, products, and operations, as well as for researchers and practitioners interested in the intersection of technology, innovation management and sustainability assessment. Manufacturing companies can improve their sustainability assessment practices in technology development by following the design propositions discussed in this study, namely.

- Design generic (Kerr et al., 2013) sustainability assessment tools that can be integrated into the technology development process (Nijssen and Frambach, 2000) used by non-sustainability experts (O'Hare, 2010).

- Implement the assessment as a facilitated workshop (Franco and Montibeller, 2010) involving a diverse set of stakeholders in the evaluation itself, including the decision-maker (Kerr et al., 2013).
- Employ multiple leading indicators (Kravchenko et al., 2020b; Saidani et al., 2021) in simple scoring methods (McAloone and Pigosso, 2018), instead of simplified single measures (Mitchell et al., 2022), avoiding overdependence on quantitative data (Chebaeva et al., 2021) that is often not available or reliable in early-stage projects.
- Employ scenario and foresight techniques to systematically incorporate internal and external uncertainties in the assessment (Bisinella et al., 2021; Parolin et al., 2023) and consider possible trade-offs (Schlüter et al., 2023) when interpreting the results.

Additional recommendations to practice were also developed, stemming from current gaps in SA methods compared to TA methods.

- Use simplified approaches to uncertainty quantification and streamlined MCDA methods in sustainability-focused TA tools.
- Develop flexible and modular tools, consisting of a general form that can be made specific according to the needs of a company or industry.
- Include circular economy principles into the sustainability assessment by, for example, introducing circularity leading indicators.
- Design the assessment tools around the technology development process and be aware of organizational factors that may affect its operationalization.

This review has limitations, mainly related to publication bias. There might be other TA methods in use in manufacturing companies, which have not been published in scientific literature, and instead are available in grey literature, distributed in companies themselves, consultancies, or other organizations. Furthermore, the criteria for establishing design propositions rely on the reporting of the methods and their testing. If the testing reporting is limited in any form (e.g., due to confidentiality issues, published before industrial cases were concluded, inaccurate) the design propositions could be skewed towards methods that are easier to deploy or more popular with industry professionals. Additionally, the discussion on possible mechanisms and outcomes for the design propositions is abductive in nature and reflects a partial view of management and sustainability literature. The mechanisms proposed in this study should be interpreted as provisional and not conclusive. Finally, since simple LCA studies were excluded from the reviewed articles for being rarely applicable to technology development projects in manufacturing companies, there might be a bias for less sustainability-focused and more qualitative methods in the final findings.

Overall, this paper contributes to the field of technology management and innovation by mapping existing technology assessment tools, providing novel insights into best practices for TA, and offering practical recommendations for SA in early-stage projects. Following the framework for research on the front-end of innovation (FEI) (Eling and Herstatt, 2017), this contributes with important findings to themes *General FEI Methods and Tools* and *Idea/Concept Evaluation*, specifically to questions “Which FEI methods and tools exist and what are their benefits and drawbacks of applying these?“, “Which organizational, project, environmental, team, or other factors impact the successful application of FEI methods or tools”, and “which evaluator characteristics determine idea/concept evaluation or screening success?“.

Our study suggests several avenues for future research in this area. One important direction would be to further refine the design principles we proposed for integrating sustainability considerations into technology assessment methods, testing their applicability in different contexts and industries. Testing of design propositions could also scrutinize the conflicts between best practices in methods targeted for sustainability versus generic ones, reconciling the divergent recommendations in literature. Furthermore, there is a need for research on how manufacturing companies can effectively implement sustainability assessment in their innovation processes, including the role of organizational culture, leadership, and incentives. Moreover, there is an important gap in the current suite of assessment tools when it comes to assessing circularity of technologies. Finally, future research could investigate how to successfully operationalize indicator selection, scenario planning, and uncertainty and trade-off management practices in the “fuzzy” front end of innovation for sustainability.

Supplementary material

Supplementary data to this article can be found at https://doi.org/10.11583/DTU.22884209.

Declaration of competing interest

The authors declare that they have no conflict of interest.

Data availability

The data is publicly available in the provided link.

Acknowledgments

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Appendix

Table 7
Technology assessment methods. Methods in italics were named by the authors of this study.

Code	Method	Reference	Code	Method	Reference
M0001	Qualitative evaluation	Zmijewska (2005)	M0031	Scoring + MCDM	Sviderska and Kukhta (2021)
M0002	FCF decision-tree	Żarczyński et al. (2017)	M0032	AHP + Grey	Sun et al. (2008)
M0003	Prospective LCA + TEA	Yousefzadeh and Lloyd (2021)	M0033	QSA	Subramaniam et al. (2016)
M0004	CoCoSo	Yazdani and Chatterjee (2018)	M0034	*Weighted KPI in triangular plot*	Su et al. (2019)
M0005	RS + TOPSIS	Xuan et al. (2022)	M0035	R2L framework	Stelvaga and Fortin (2022)
M0006	LCA + FCE + AHP	Xiong et al. (2020)	M0036	Morphological analysis	Spharim and Ungar (1995)
M0007	Green Assessment Method	Xie et al. (2022)	M0037	GREENSCOPE	Smith et al. (2019)
M0008	TEA + LCA framework	(Mahmud et al., 2021; Wunderlich et al., 2021)	M0038	Fuzzy-AHP	Si et al. (2020)
M0009	TAIT methodology	Williams-Byrd et al. (2016)	M0039	DEMATEL + ANP	(Shen et al., 2010, 2011, 2012)
M0010	QFD innovation evaluation	Weller et al. (2007)	M0040	*Scoring with weighting*	Shehabuddeen et al. (2006)
M0011	SCORE	Weiss and Schlenoff (2008)	M0041	LCA + Diffusion	Sharp and Miller (2016)

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Table 7 (*continued*)

Code	Method	Reference	Code	Method	Reference
M0012	START	Weisbin et al. (2004)	M0042	Participative TA	Schneider et al. (2023)
M0013	TEA with trends	Weigelt et al. (2018)	M0043	*Monetary technology appraisal*	Schmidt et al. (2018)
M0014	Entropy TOPSIS	Wang et al. (2020)	M0044	LCC + decision trees	Schlater et al. (1993)
M0015	Sustainable indicators	Wallbaum et al. (2012)	M0045	WBC	Schjaer-Jacobsen (1996)
M0016	TEA + LCA for process ind.	Villegas and Gnansounou (2008)	M0046	EKAT	Saulters et al. (2010)
M0017	BRLa	Vik et al. (2021)	M0047	Hesitant f-AHP + f-VIKOR	(Samanlioglu and Ayag, 2020)
M0018	TSA framework	Van Schoubroeck et al. (2021)	M0048	Pindar	Rovetta et al. (2006)
M0019	Social Indicators	van Haaster et al. (2017)	M0049	*Env. Index + Economic index*	Romel-Antonio et al. (2020)
M0020	TIES	(Preisner et al., 2002; Utturwar et al., 2002)	M0050	MEPT	Rezagholi and Frey (2000)
M0021	LCC + LCA + FCP	Umer et al. (2017)	M0051	*Selection of criteria using SWOT*	Reiβmann et al. (2018)
M0022	Upscalling in ex-ante LCA	(Kawajiri et al., 2020; Tsoy et al., 2020)	M0052	Expert evaluation + Fuzzy sets	Reinhart et al. (2011)
M0023	Weighted LCA and Benefits	Tsang et al. (2014)	M0053	Anticipatory LCA + outranking	Ravikumar et al. (2018)
M0024	Attractiveness score	Tran et al. (2008)	M0054	Modified TOPSIS	Rafiaani et al. (2020)
M0025	Prospective LCA	Thonemann et al. (2020)	M0055	MAPL-OET	Radpour et al. (2021)
M0026	ETEA	Thomassen et al. (2019)	M0056	Innovation assessment + TRIZ	Pryda et al. (2018)
M0027	Technology maturity	Theodossiadis and Zaeh (2017)	M0057	Stochastic Fuzzy ANP	Promentilla et al. (2017)
M0028	QTA	Tejtel et al. (2005)	M0058	*Technical TA*	Ponchak et al. (1990)
M0029	Delphi + AHP	Tang et al. (2014)	M0059	LYFE	Pohya et al. (2021)
M0030	*Persona pairwise comparison*	Talbot et al. (2021)	M0060	TBL KPIs + backcasting	Partidario and Vergragt (2002)
M0061	Interviews	Palm et al. (2013)	M0092	Manuf. tech. readiness ass. 1	Jones et al. (2012)
M0062	SWBVA	Ordoobadi and Mulvaney (2001a)	M0093	Manuf. tech. readiness ass. 2	Jones et al. (2012)
M0063	Bayesian	Oliveira et al. (2021)	M0094	Integration via TRL	Jimenez and Mavris (2013)
M0064	Ntech + GDSS	Noori (1995)	M0095	CBA + AHP	Ivanco et al. (2016)
M0065	Response modeling	Nixon and Mavris (2002)	M0096	ES2050 approach	Haase et al. (2022)
M0066	*Group assessment of criteria*	Nanyam et al. (2015)	M0097	TQ	Huyse (2014)
M0067	R-TODIM	Mousavi et al. (2022)	M0098	*Ares project approach*	Hueter and Tyson (2010)
M0068	CBA	Metzner et al. (2018)	M0099	Regression model	Hu et al. (2019)
M0069	TPL	Mendoza et al. (2022)	M0100	*Strategic evaluation*	Hou et al. (2008)
M0070	TIES + TOPSIS	McNabb et al. (2019)	M0101	TTRL	Holt (2007)
M0071	*Maturity + innovation*	Mazurkiewicz et al. (2015)	M0102	*TEA + LCA with monte carlo*	Hoffmann et al. (2004)
M0072	CSA	(N. E. Matthews et al., 2019b)	M0103	*Disruptive innovation checklist*	Hang et al. (2011)
M0073	TCM	Mascarin and Lynn Marallo (1996)	M0104	Sustainability guidance to TRL	Hallstedt and Pigosso (2017)
M0074	TRRA	Mankins (2009)	M0105	TOPSIS + TRL	Halicka (2020)
M0075	MIVES	Lizarralde et al. (2022)	M0106	*Roadmap builder*	(Güemes-Castorena et al., 2013; Güemes-Castorena and Uscanga-Castillo, 2014)
M0076	Linguistic MCDM	Liu et al. (2019)	M0107	DII	Guo et al. (2019)
M0077	Fuzzy BWM	Li et al. (2021)	M0108	*Future market potential*	Gu and Huang (2009)
M0078	*Normalized indicators*	Li et al. (2013)	M0109	LCA Polygon	Georgakellos (2006)
M0079	MOMT	Li et al. (2019)	M0110	Monnier's Innovation Matrix (MIM)	Gayrard and Monnier (2010)
M0080	Three-stage fuzzy MCDM	Lee and James Chou (2016)	M0111	IISA	Gasde et al. (2020b)
M0081	LCA + TEA	Lee et al. (2021)	M0112	*Risk based TEA and LCA*	Gargalo et al. (2016)
M0082	*Weighted sum of indicators*	Laforest (2014)	M0113	Innovation impact map	(Feland, 2003)
M0083	*MCDA for wireless technologies*	Krapivina et al. (2019)	M0114	PO + DEA + TW	Fazeli et al. (2011)
M0084	Risk + FTA	Koivisto et al. (2009)	M0115	*Configurable toolset for TA*	Farrukh and Holgado (2020)
M0085	TIF	Kirby and Mavris (2002)	M0116	*Supply-chain TA*	(Farooq and O'Brien, 2015)
M0086	PRISM	Kim and Chang (2013)	M0117	*Composite objectives optimization*	Eapen et al. (2021)
M0087	*Innovation scorecard*	Kerka et al. (2009)	M0118	*Tactical and operational AHP*	Ertay (2002)
M0088	Neural network + AHP	Kara and Berkol (2014)	M0119	*Exergy TA*	Dewulf and Van Langenhove (2005)
M0089	*Sequential TEA + LCA*	Kadhum et al. (2018)	M0120	TDE	Daim et al. (2018)
M0090	Modified QFD	Justel et al. (2007)	M0121	AHP + Scoring	Daim and Intarode (2009)
M0091	*Technical implementation risk*	Jones and Reveley (2014)	M0122	Grey Possibility Degree (GPD)	Dabbaghi (2020)
M0123	Prospective env. analysis	Cooper and Gutowski (2020)	M0144	TIES + genetic algorithm	Roth and Patel (2004)
M0124	Sustainability Impact Index (SII)	(Saphir A. Choudry et al., 2018d)	M0145	Science advisory committee	Rosenfelder (1992)
M0125	*Economic assessment*	(Saphir A. Choudry et al., 2018c)	M0146	Fuzzy AHP + VIKOR	Ren and Lützen (2015)
M0126	Performance indicators	(Saphir A. Choudry et al., 2018b)	M0147	*3-D space for bus. processes*	Pretorius and de Wet (2000)
M0127	*Monetary vs non-monetary*	(Saphir A. Choudry et al., 2018a)	M0148	*Relative judgment + scenarios*	Partidário and Vergragt (2001)
M0128	*Technological assessment*	(S. A. Choudry et al., 2018)	M0149	SWBVA	Ordoobadi and Mulvaney (2001b)
M0129	Delphi + fuzzy AHP	Cho and Lee (2013)	M0150	COPRAS-G	Nath and Sarkar (2017)
M0130	*Strategic technology evaluation*	Chifos and Jain (1997)	M0151	EVAMIX	Nath and Sarkar (2017)

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Table 7 (*continued*)

Code	Method	Reference	Code	Method	Reference
M0131	Visualized scenario analysis	Chen et al. (2015)	M0152	STAR	McGrath and MacMillan (2000)
M0132	Maturity of micro/nano tech.	Brousseau et al. (2010)	M0153	*Tech. portfolio assessment*	Jolly (2008)
M0133	AMICAI	Brandl et al. (2020)	M0154	TOPSIS + CBA	Chau and Parkan (1995)
M0134	*Multi-indicator biochemical ass.*	Bienert et al. (2019)	M0155	ORWARE (LCC + LCA + MFA)	Assefa et al. (2005)
M0135	LCA of emerging technologies	Bergerson et al. (2020)	M0156	DEA with ordinal data	Amin and Emrouznejad (2013)
M0136	*Multi-indicator e-waste ass.*	Barletta et al. (2016)	M0157	*Scoring methods*	Mitchell et al. (2022)
M0137	MAUT	Bard and Feinberg (1989)	M0158	Picture fuzzy rough sets (PFRS)	Dinçer et al. (2022)
M0138	QFD-AHP	Bagassi et al. (2020)	M0159	*TEA for pesticide dispersion*	Loh et al. (2022)
M0139	TRL + CRI	Animah and Shafiee (2018)	M0160	*KPI selection*	Cabeza et al. (2021)
M0140	QFD + FMEA	Almannai et al. (2008)	M0161	IO Hybrid LCSA	Elagouz et al. (2022)
M0141	*TEA + LCA + sensit. and uncert.*	Agbor et al. (2016)	M0162	LCA + scaling up	Rai et al. (2022)
M0142	TEA + LCA for CCU	Zimmermann et al. (2020)	M0163	GBWM	Tavana et al. (2023)
M0143	DEA with double frontiers	Wang and Chin (2009)	M0164	*Framework for infrastructure ass.*	Chan et al. (2022)

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