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Scenario building guidelines for sustainable innovation

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

Abstract
The integration of sustainability into highly uncertain technology development is key to support manufacturing companies to reduce their environmental impacts. The use of future scenarios to support decision-making in early design for sustainability is promising, but there is a lack of systematic guidelines on how to build them. Through literature review and empirical research scenario-building guidelines were designed. The guidelines are step-by-step activities to be performed in workshops. Results suggest the guidelines were successful in building consistent, plausible, and useful scenarios.

Keywords: technology development, futures studies, ecodesign, scenarios, uncertainty

1. Introduction

Manufacturing companies are increasingly considering sustainability and circularity in their front-end of innovation process and decision-making (Parolin et al., 2023a). Technology development plays an important role towards more sustainable innovation, as technology development usually takes place before product development, with longer timeframes and higher complexity (Brilhuis-Meijer et al., 2016). In addition to increasing complexity, integrating sustainability into the early stages of innovation faces challenges such as high uncertainty, lack of data, and lack of formal guidance (Parolin et al., 2023b). These challenges are particularly relevant in technology development as an exploratory process that deals with a high level of abstraction regarding later applications and market adoption of the technologies in development (Cooper, 2006).
Future scenarios have been argued to be an effective method to support decision-making in a highly uncertain environment, as they can support the exploration of a range of possible futures in which strategic pathways can be prepared (Chermack, 2004). They first appeared in the 1960s with American military strategist Herman Kahn's work on geostrategy and potential escalation of military conflicts. Since then, scenarios have become a major concept and methodology in foresight studies, introduced as a tool for strategic planning in public and private sectors (Van der Heijden, 1996). Their use has increasingly been spread in businesses in the US and Europe but gained even more popularity in the middle of the 1980s with Pierre Wack's publication about the Royal Dutch Shell success story thanks to scenario planning (Varum and Melo, 2010).
While scenarios seem to support sustainability integration into technology development, it remains an emergent discipline, with scenarios being described as "methodological chaos" (Bradfield et al., 2005). There is a lack of a step-by-step approach to consider contextual factors and broader sources of uncertainties - which are common in technology development - when generating and using scenarios (Schwartz, 1991). The motivation of this research is therefore to provide support for decision-making when assessing sustainability in technology development. To perform this task, the following main research question will be discussed: **how can future scenarios support the evaluation of sustainability in technology development?**

This study aims at providing support guidelines for the creation and use of sustainability scenarios by engineers and design practitioners working in technology development in manufacturing companies. The scenario building guidelines were based on existing research and an industrial case study.
This paper is structured as follows: after presenting the methodology of the study (Section 2), the findings and gaps identified from the literature review are highlighted (Section 3). Then, the guidelines are presented (Section 4) and the results of a pilot in the case company are discussed (Section 5).

2. Methodology

The methodology of this study is based on the Design Research Methodology (DRM), developed by Blessing and Chakrabarti (2009). The support developed in this research consists of guidelines to build future scenarios for manufacturing companies to better integrate sustainability considerations into technology development. The support was developed, tested, and evaluated in collaboration with a case company (Table 1), but with the aim of being adaptable to any manufacturing company. This study is part of an ongoing project with the case company, an international manufacturing firm based in Denmark undergoing an organizational transition towards increased environmental sustainability in its value chain. The methodology consists of four main stages:

- The **Research Clarification (RC)** aims to explore and provide an initial understanding of future scenarios by identifying the relevant contribution from the existing body of literature. Definitions, typologies, and schools of thought were reviewed.
- The **Descriptive Study-I (DS-I)** explores in further detail the relationship between the field of future scenarios reviewed in the RC and the need to explore sustainability in the technology development process in manufacturing companies. An in-depth literature review is performed to identify the existing methods to build scenarios and insights are gathered through interviews with experts from the case company to understand the overall development context and the potential contribution of future scenarios. This provides a sound basis for the following stage for the effective development of the guidelines.
- The **Prescriptive Study's (PS)** objective is to develop, based on the knowledge and gaps identified in the DS- I, a support to build future scenarios when integrating sustainability into technology development. This support is developed in an iterative way as guidelines to apply in a workshop setup, following the requirements and best practices from the case company. After filtering and discussing the suitable scenario-building methods to draw inspiration from, the guidelines are adapted and refined based on the requirements from the case company.
- The **Descriptive Study II (DS-II)** evaluates the support developed in the PS, i.e., the scenario-building guidelines (SBG) through empirical methods, to identify implications and suggestions for improving the support. The evaluation of the SBG is conducted through a workshop held at the case company on a concrete technology development case, with relevant experts to assess the usability and usefulness of the SBG and provide ways for improvement.

Table 1. Sequential steps undertaken towards the development of scenario building guidelines

Activity	Output
Review of literature	Description of 16 methods for building scenarios
Interviews at the case company	Gaps and requirements
Analysis of existing methods and gaps	Screening and narrowed selection of 5 methods
Internal tests among co-authors	Initial guidelines and refined requirements
Comparison and discussion with case company	Selected 1 method
Adaptation based on gaps	Iteration of the guidelines based on the selected method
Evaluation workshop with case company	Feedback for improvement
Guidelines update from feedback	Guidebook summarising the updated guidelines

3. The potential of scenarios for sustainable innovation

This section presents results from literature review activities undertaken during RC and part of DS-I.

As part of the front-end of innovation, technology development can be described as creating "new knowledge, new technology, a technical capability, or a technological platform" (Cooper, 2006). The output of a technology development project can range from improved manufacturing processes, to new material capabilities, to innovative product concepts. It is a very uncertain future-oriented process exploring a wide range of possibilities and application contexts (Parolin et al., 2023b).

Amer et al. (2013), Bishop et al. (2007), and Wilder et al. (2021) have provided reviews and described various methods related to scenario-building and planning. Wiebe et al. (2018) highlight the recurrence of sustainability evaluation in scenario studies relating to climate change, technological futures, socioeconomics, or policy formulation. Höjer et al. (2008) reviewed the different methods to analyse environmental impacts and the suitable scenarios methods to use. However, Duinker and Greig (2007) reveal that even though many studies combine scenarios and sustainability assessment, few manage to perform it in a formal way. Indeed, organizations face great challenges when considering sustainability in future-oriented activities, all the more in the early stages of innovation such as technology development (Parolin, McAloone, Eriksen, et al., 2023).

It is argued that scenarios can support early-stage decision making by:

- Managing, eliciting, and registering tacit knowledge. It may support decision-makers by providing a platform for discussions and involving experts' knowledge (Wiebe et al., 2018). It allows them to embrace uncertainty and respond to challenges in decision-making such as breaking mental models, processing information, and reaching a shared understanding (Chermack, 2004).
- Creating a shared frame of reference and narrative across the company. Building scenarios involves the collection, analysis, and discussion of diverse information during collective and participatory activities, and the diversity of organizational functions involved during these activities is crucial to its success (Fahey and Randall, 1998).
- Challenging existing beliefs and assumptions. It allows one to challenge and break current mental models during strategic conversations by identifying new issues and problems that may arise in the future (Varum and Melo, 2010).
- Mapping uncertain contextual factors. Scanning the macro-environment or "context in which an organization operates and will operate" is essential to support the decision-making process (Chermack, 2004) and is a common first step in several scenario-building methods. Furthermore, it is widely considered that sustainability transitions in companies are highly dependent not only on technological aspects, but also on societal and political feasibility and other systemic aspects such as infrastructure and maturity (Turnheim and Nykvist, 2019). While many templates to map these contextual factors exist, the PESTEL (Political, Economic, Sociocultural, Technological, Environmental, and Legal) framework provides a systematic way to analyse the macro-environment (Yüksel, 2012).

4. Guidelines for building future scenarios

The SBG are developed as part of a sustainability screening toolkit to evaluate the sustainability of under-development technologies. They are written down as specific step-by-step tasks, supported with definitions of the key concepts involved, and with visual templates. As a core activity of the sustainability screening, the guidelines are designed for a multidisciplinary audience of experts and technology developers, applied in a facilitated workshop lasting up to 3 hours. They have been gathered and summarized as guidebook for practitioners (available as supplementary material). The SBG are presented in the following sections, starting the gaps and requirements, and a brief clarification of the terminology used in the guidelines. This section covers mostly activities from DS-I and PS-I.

While the context of this study has a strong focus on environmental sustainability, the use of the guidelines can be extended to the broader concept of sustainability.

4.1. Gaps in scenario building methods

Insights on the processes, methods, expectations, and needs of the company have been collected through interviews with experts from the case company. By linking literature and interviews' findings, three main gaps have then been identified:

- Technology development is planned considering a short-term horizon, but environmental targets are established in the long-term. No connection is made between these short and long-term futures. Future scenarios can support futures-thinking in technology development and could help extend its scope towards mid/long-term future, aligning it to strategic considerations.
- The analysis of the macro-environment in which an organization operates and will operate is essential to support decision-making and a crucial step when building future scenarios. There is however no systematic guidance on how to map these contextual factors in connection to scenario building.
- The use of scenarios in sustainability assessment is often not formalised. The need is then to find an appropriate scenario-building method to combine with the sustainability assessment performed via the screening toolkit.

These gaps served as the starting point and backbone requirements to design the guidelines.

4.2. Context and key concepts

To clarify the meaning of the key concepts used in the guidelines, some definitions are given:

- **Project and Decision**: The Project refers to the specific technology development project being considered and more specifically in the scenario-building activity. The Decision refers to the goal of the Project, implying going through a decision-making process. In technology development, this decision typically consists in fostering the development of one technology over others.
- **(Sustainability) Criteria:** The Sustainability Criteria are the crucial factors on which the Decision will be based. These criteria are most likely to be internal to the organization and linked with its micro-environment, i.e., its financial state, manufacturing process, supply chain, etc. Sustainability Criteria are internal, crucial, and decisional factors based on sustainability.
- **Driving Forces:** The Driving Forces are the external factors of the organization that influence the state or value of the Sustainability Criteria. These can be identified in the macro-environment in which the organization operates, i.e., economic growth, governmental policies, consumer habits, etc.
- ***Scenario Dimensions***: In the second step of the Guidelines, Scenario Dimensions refer to the Driving Forces that have been selected and form the axes of the Scenario Space in the third step.

4.3. The guidelines

The SBG are mainly inspired by the original Global Business Network method introduced by Schwartz (1991). They differ from the existing methods by focusing on sustainability and technology development activities. This is achieved by connecting their input and output with other technology development and sustainability screening activities, including a systematic and structured way to identify sustainability Driving Forces, and performing a consistency check inspired from the morphological analysis (Johansen, 2018). Finally, templates have been developed to allow the generation of scenarios as a participatory group activity during workshops.

The SBG include five steps to build future scenarios:

1. Scanning driving forces from the macro-environment
2. Selecting the scenario dimensions
3. Building the scenario space
4. Defining consistent logics
5. Fleshing out the scenarios

To illustrate the SBG, a dummy (fictional) case will be developed along the steps' description to serve as an example (indicated in *italics*).

4.3.1. Initial inputs: Sustainability Criteria, Project, and Future Scopes

The scenario-building process starts after the two first steps of the sustainability screening, where the Sustainability Criteria, the Project Scope, and the Future Scope are defined. These are assumed as inputs for the SBG. They are essential for participants to have a great understanding of the Project, the Decision, the challenges at stake and the focus of the study.
Example: a technology development project studies the potential transition from current lithium batteries to new-generation silicon-based batteries. The decision to make is to continue with traditional lithium batteries or to switch to silicon-based batteries. To explore what the future of those technologies can be, scenarios will be generated in a five to ten years future, when the new technology is expected to mature. For the company based in Europe, the strategic management department has identified key factors that would influence the decision from an environmental sustainability perspective. These criteria are the following: Material Use, Recyclability, Lifespan, and Yield (Energy in use phase).

4.3.2. Step 1: scanning driving forces from the macro-environment

This first step of the scenario-building process starts with an analysis of the external (contextual) factors. They are driving forces from the macro-environment level that might influence the criteria used in the sustainability assessment. The question that this step tries to answer is what in the macro-environment can influence the sustainability criteria.
For each criterion, the participants write down the driving forces they think are relevant. To inspire participants and to organize these driving forces, the PESTEL analysis template (Figure 1) is used. It provides six categories of driving forces: Political, Environmental, Socio-Cultural, Technological, Economical, and Legal. Participants can then successively reflect on each of these categories. Another useful framework to map driving forces could be that of sustainability transitions and the factors that influence the feasibility of a sustainability transition pathway realization: political feasibility, societal acceptability, system integration and infrastructure, and maturity of options (Turnheim and Nykvist, 2019).
The identified driving forces are sorted in the PESTEL template (Figure 1) and each of them is discussed collectively. The latter can be refined, combined, or removed and new ones can be found during the discussion.
Example: for each of the previous Sustainability Criteria, some Driving Forces are identified and gathered in the template (Figure 1). For the material use, as most of the lithium is produced and exported by China, the political and economic relations with the country are of great influence of the use of this material. Moreover, the lithium resources availability will influence the decision in the future. For Recyclability, the most influential factors will be the consumers' habits on recycling and the potential regulations on the end-of-life of products. Regarding the Lifespan, it will be influenced by the properties loss rate but also the way consumers use and charge their batteries and how technologies to maintain lithium batteries evolve. Finally, the Yield will be influenced by the global temperature of use which can be influenced by climate change.

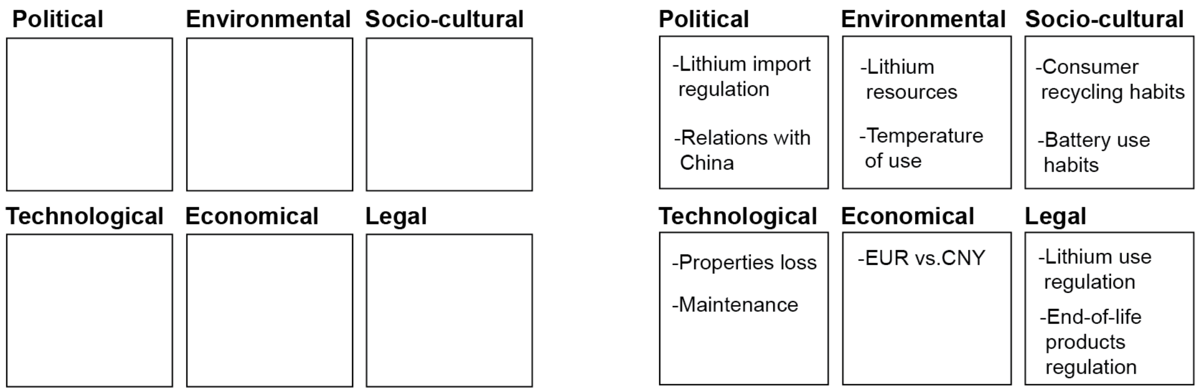

Figure 1. PESTEL template and example for step 1 of the SBG

4.3.3. Step 2: selecting the scenario dimensions

The second step aims at identifying and selecting the most crucial of the identified driving forces to form the axes of the scenario space, which are called scenario dimensions. To select these scenario dimensions, each driving forces is assessed in terms of importance to the project and uncertainty level. To rank them, a two dimensions selection matrix is used (Figure 2). One by one, the driving forces identified in Step 1 are placed in the matrix, relatively to the others.

Once the ranking is done, the most important and uncertain driving forces are selected. These can be found in the top right corner of the matrix. Usually, two of them are selected but alternatively it can also be one or three. The number of scenarios generated will depend on the number of chosen driving forces (see Step 3). There is no consensus on the ideal number of scenarios but various researchers on futures studies have usual recommendations from three to six different scenarios (Amer et al., 2013). Therefore, when selecting the driving forces, the participants need to answer the question of what pair (or single or set) of driving forces will make a great difference among the scenarios.

Example: political and economic relations with China seem to be decisive for the future of battery technologies. Being the first producer and exporter of lithium, and with political tensions arising with the Western countries, the relations are very uncertain, though important. Moreover, the new technologies of maintenance will play a big role in the longevity and competitiveness of lithium-based batteries. As some of the most uncertain and important driving forces, not correlated at first glance, this pair of driving forces is likely to make a great difference in the generated scenarios.

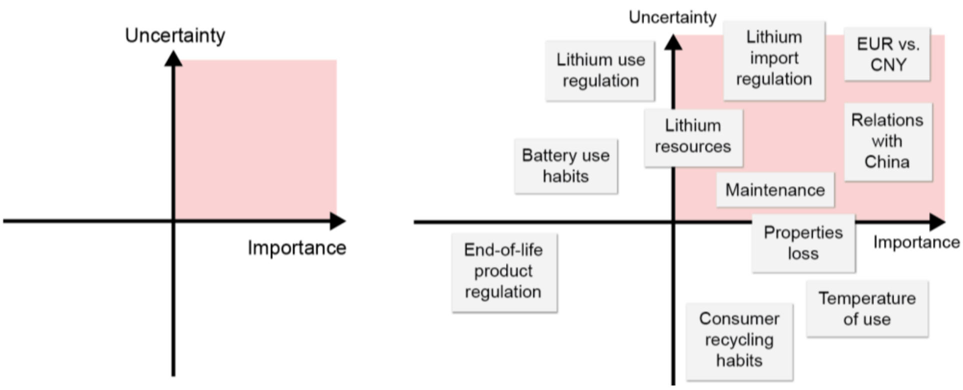

Figure 2. Ranking matrix and example of ranked driving forces for step 2 of the SBG

4.3.4. Step 3: building the scenario space

Once the scenario dimensions have been selected, the scenario space can be generated (Figure 3). This step is meant to help visualize the different scenarios that will be generated. Each scenario dimension will be assessed on a binary scale (high or low). Depending on the number selected in Step 2, the scenario space will either be one single axis, a two dimensions matrix, or a three dimensions volume, resulting in two, four, or eight scenarios, respectively.

Example: considering two scenario dimensions, four scenarios will be generated in the Scenario Space. While the maintenance technologies available will be assessed from low to high, relations with China will be assessed from bad to good.

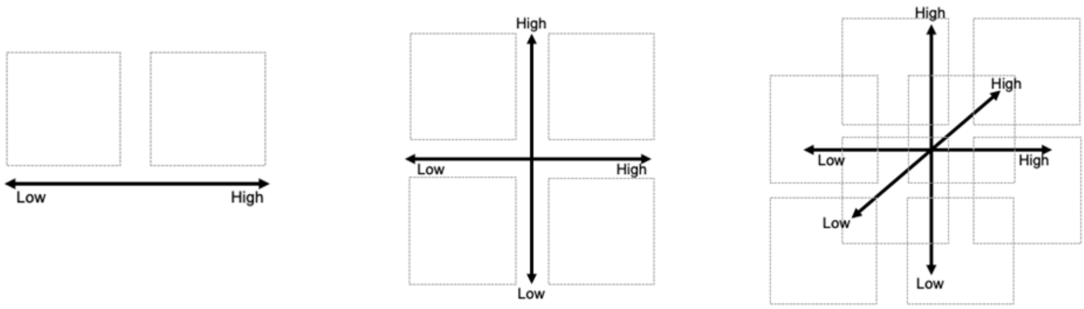

Figure 3. From left to right: scenario spaces with 1, 2, and 3 dimensions, for step 3 of the SBG

4.3.5. Step 4: defining consistent logics

After having built the scenario space, the following step is to define the scenario logics generated and check their consistency. Indeed, with the binary scale used, each cell of the scenario space represents a unique combination of values of the scenario dimensions, thus generating one scenario logic.

For each cell, participants review the combination of values taken and check for their consistency. The consistency is verified based on logical consistency (i.e., if the combination of values and their relationships are not contradictory), and empirical consistency (i.e., the combination of values is empirically possible). If some of the logics are judged inconsistent, they will no longer be considered in the following step. For the consistent scenarios, a short title encompassing the logic is given to support the next step. This is illustrated in Figure 4.

Example: the scenario space is built with two dimensions. A first review of the values taken in each cell proves to be consistent and some first titles can be attributed to the scenarios: Loose Control, Lithium Power, Silicon Valley, and As-Is.

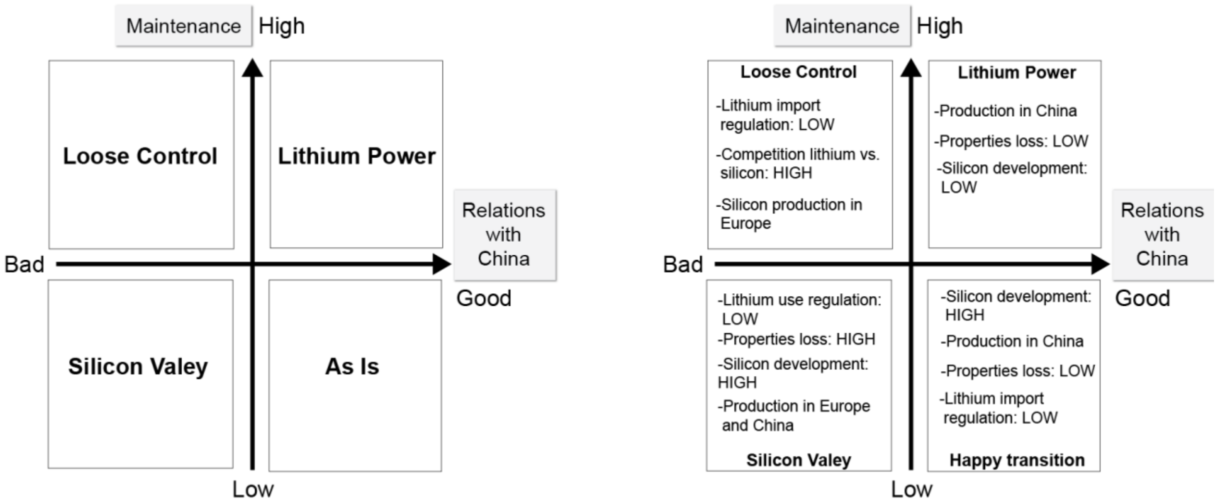

Figure 4. Example of two dimensions of scenario space, with fleshed out scenarios on the right, as part of steps 4 and 5 of the SBG

4.3.6. Step 5: fleshing out the scenarios

This last step of the scenario-building process consists in developing in more detail the scenario logics established earlier. Once the logics have been defined and named with titles, participants assess the other relevant driving forces that have been identified in Step 1 but not selected in Step 2, within a specific logic. The process is repeated for each scenario logic defined in Step 4.

Then, a narrative in the form of a few sentences is written, encompassing the overall logic of the scenario and the specific details elaborated in this step. Finally, the titles of the scenarios can be revised to provide a better description and understanding (Figure 4).

Example: each scenario logic is reviewed in detail, assessing other driving forces within the scenario. Then the following narratives are developed for each scenario and the corresponding titles are revised:

- *Loose Control: The relations between China and Europe are so bad that Europe can't get their hand on lithium. China takes over the control of lithium supplies, developing high maintenance technologies, allowing a longer lifespan and bringing high competitiveness against silicon batteries. Europe has to develop its own production lines for silicon batteries.*
- *Lithium Power: Lithium batteries stay on top of the battery technologies offering the best performance thanks to new maintenance processes. It allows a longer lifespan and better recyclability.*
- *The Silicon Race: As China gets the monopoly on lithium use and lithium cannot catch up with silicon technology, lithium is on the decline and silicon batteries become the reference market*

products. The bad relations limit the import/export of goods, so Europe must start its own production, competing with the Chinese one. A technological progress race is triggered.

- *Happy Transition: lithium performs with poor maintenance and got out beaten by silicon which has better performance. China becomes a production leader and products are exported all over the world. The good relations allow Europe and the company to import their technology and products.*

4.3.7. Output

The output of these guidelines is a set of generated, consistent, and detailed scenarios narratives (which can range from 2 to 8 scenarios), specific to a related project. These scenarios will later be used in the sustainability screening process as a basis for the assessment of a technology.

5. Evaluation and discussion

A pilot workshop was conducted at the case company where the SBG were applied alongside the sustainability screening tool in an ongoing technology development project. Observations and feedback were captured to evaluate the usefulness and usability of the support, namely the SBG. This section covers mostly the undertaken during DS-II.

As results of the pilot workshop, the interest and potential of foresight by using scenarios were confirmed. The SBG succeeded in generating the expected outcome, that is, building a set of plausible, consistent, and different scenarios. Usefulness results appear to be better than for usability, reflecting a strategic potential for the SBG. There is a good potential for the SBG in contributing to integrating sustainability into technology development.

5.1. Usability

Even though the main scenario-building method from which the SBG were adapted had been selected for its low complexity, exploring the future remains counter-intuitive and the increasing level of uncertainty in the process was not straightforward for all the participants. Moreover, too little time was available for each step, which was reflected in the observations made during the workshop. There was a limited amount of time to run the workshop (ca. 3 hours) and an initial part of that time was dedicated to introducing the toolkit and the project. Thus, there is room for improvement for the SBG when it comes to timing and presentation. Ideally, they require a more detailed description of the tasks and more preparation before they are to be used. This shortcoming can be addressed by providing the guidelines in advance with an introduction to the project considered, the purpose of the processes and more specifically, a description of their expected contribution, the type of tasks involved, and examples.

5.2. Usefulness

The quality of the outcome of the SBG seemed to be related to the type of project in which they were employed. As the maturity of a project increases, the uncertainty level decreases, reducing the need to explore the future and therefore using future scenarios. This can be analysed in regard to the classification of innovation projects, which can be incremental, evolutionary, or radical. Future scenarios would tend to be more useful for radical innovation technology development projects involving large-scale changes within the company, for which the uncertainty is at the highest. Thus, the degree to which the SBG are applicable or desirable for a specific project needs to be reflected beforehand, according to how radical or incremental the innovation is.

Finally, the connection of generated scenarios and the evaluation of sustainability was compromised as participants could not see large differences when evaluating the sustainability indicators in the alternative scenarios. This prevented the execution of the next activities in the screening process and brought the workshop to an end. To improve this connection between scenario-building and the evaluation of sustainability indicators (i.e., make sure that the scenarios influence the sustainability criteria), two options can be considered: defining the indicators after building the scenarios to adjust the precision and relevance of the indicators from the scenarios' level of detail or amplifying the scenarios and adjusting their level of detail to the defined indicators by proceeding to a more detailed "fleshing out" with further activities.

5.3. Limitations of the guidelines and implications

First, this study was framed in the very specific context of an ongoing project in collaboration with a case company. The support created is meant to be one of the main activities of the toolkit exploring the sustainability of under-development technologies. This context limits the contribution to the research question. The type of sustainability assessment is given by the screening toolkit, and the technology development process is defined by the case company. Thus, the research question could be answered to a larger extent by exploring the use of different scenario-building methods with different types of sustainability assessment and also within different processes. Although designed in this specific context, the guidelines remain generic, combining existing methods to build scenarios. They are therefore applicable to any other manufacturing companies and not limited to technology development.

Secondly, this study relies on a literature review of scenario-building methods identified in studies and on other reviews. However, the identified methods are not exhaustive. Some were not considered due to a lack of available data. Used essentially for strategic purposes, variations of scenario-building methods are developed to meet specific organizations' needs. It results in a great number of variants leading sometimes to confusion or contradiction. Thus, a more systematic literature review could potentially identify other scenario-building methods that would also fit the requirements for the support.

Finally, one of the main gaps identified was the missing connection between the case company's current technology planning in the short term and their environmental targets set in the long-term future. Although the SBG are meant to explore the future on a range in-between those two futures, they don't address this connection in their output. It is not their direct purpose to make this connection but the strategic management's. However, SBG could support this task if scenarios generated were documented and used as a database to imagine the different ways to make this connection.

6. Conclusion

This research contributes through both literature and industry by understanding how future scenarios can support the evaluation of sustainability in technology development, By developing scenario-building guidelines (SBG) in collaboration with a manufacturing company, this study has developed a step-by-step approach to systematically consider uncertainties and risks when creating future scenarios for integrating sustainability into innovation activities in manufacturing companies.

The development of qualitative and participatory SBG serves the purpose of supporting a multidisciplinary audience to generate original scenarios within the context of sustainability screening in technology development. The five-step guidelines were iteratively elaborated, initially based on the well-known Global Business Network method. The sustainability criteria of the company are used as the input of scenario building. The PESTEL analysis and a sustainability transitions framework are used to provide a systematic exploration of the macro-environment's influences. A consistency check of the scenario logics has also been added. A workshop conducted at the case company has enabled the evaluation of usability and usefulness of the SBG in an ongoing technology project. While a potential in the usefulness of the SBG was confirmed, the guidelines still have room for improvement.

Through ongoing refinement and practise, the SBG can become a systematic method to explore the sustainable futures of new technologies. There is a great potential for SBG, and scenarios in general, to become a gold standard in the manufacturing companies' strategic innovation process and technology development to reach long-term sustainability targets.

Supplementary material

A guidebook containing the SBG is available at https://doi.org/10.11583/DTU.24218916

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