THE EFFECTS OF SCENARIOS ON DECISION-MAKING QUALITY IN EARLY DESIGN – AN EMPIRICAL STUDY

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ABSTRACT

Scenario planning is often used in design practice to foster futures thinking, reduce uncertainties and improve decision-making. Scenarios are especially relevant for innovation activities in manufacturing companies, such as technology development, a particularly uncertain process where many trade-offs occur. This study is, to the authors knowledge, the first to empirically measure the effect of scenarios in decision-making quality, in the context of technology development. In a quasi-experiment, engineers from a manufacturing company and university students were independently asked to analyse a trade-off situation between environmental and financial aspects of a technology concept, with and without scenarios. The quality of decision-making quality for control and experiment groups was measured through a standardized questionnaire. The results show that scenarios had a positive impact in 6 of the 7 quality decision-making practices (QMDP), although the effect size is small. The results suggest that both expert and novice designers may benefit from using scenario planning when performing early-stage design activities by having awareness of the decision context, a more structured decision process, and clearer decision criteria.

Keywords: Futures studies, Technology Development, Sustainability, Decision making, Early design phases

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1 INTRODUCTION

Innovation and technologies play a major role in the competitiveness of manufacturing companies (Phaal *et al.*, 2001). Technology development is one of the activities that often takes place in the front-end of innovation, leading companies to explore new product or process development opportunities (Cooper, 2006; Koen *et al.*, 2001). The technology development process is, as a very early design activity, critical to the success of the commercial projects which it will shape (Aristodemou *et al.*, 2019). Thus, special attention must be given to the decisions that take place during technology development. These decisions are traditionally made based on short-term financial prospects of the technology being developed (Cooper, 2006). However, companies and other organizations are increasingly taking sustainability and circular economy matters into account in their decision-making practices (Villamil *et al.*, 2022), which increases the complexity of the decision-making process.

Decision-makers in the technology development process face significant uncertainty and complexity, whether considering only financial or also sustainability information (Mitchell *et al.*, 2022; Villamil *et al.*, 2022). These projects tend to be riskier and follow less formalised processes (when comparedto product development projects), which amplifies the uncertainty issues (Aristodemou *et al.*, 2019; Koen *et al.*, 2001). A major source of uncertainty, especially in relation to sustainability, stems from the lack of context information - as technology development projects can be foundational to new product platforms or even new businesses (Cooper, 2006), one technology may be used in several applications with different degrees of social and environmental impacts. Without a clear picture of the socio-technical context, decision-makers resort to intuition when faced with trade-offs (Mitchell *et al.*, 2022).

Methods stemming from futures studies have been proposed as possible ways to explore uncertainties, lack of context knowledge and trade-offs in early-stage design. More specifically, scenario planning has been argued for as a promising method for better decision-making in highly uncertain settings (Chermack, 2004), such as the evaluation of a new technology. Many case studies and other qualitative research have been done exploring the correlation between scenario planning and decision-making (Doualle et al., 2019; Harries, 2003), but little empirical research has been done on measuring its effect. To the authors' knowledge, so far, no empirical study has been able to quantify improvements in the quality of decision making when scenario planning was used to assess technologies in early-design settings. Bodin et al. (2016) have conducted a quasi-experiment to determine the effect of scenario planning on decision-making style. In the study, participants who engaged in scenario planning were less spontaneous, while being more intuitive and dependant on other stakeholders. However, this change in decision-making style does not clearly translate to a better or worse decision-making quality.

Thus, the goal of this paper is to evaluate the effect of scenarios in decision-making quality in engineering design and innovation activities, via a quasi-experimental approach. Motivated by the challenge of assessing the sustainability of new technologies in manufacturing companies, this study aims to answer the following research question: *to what extent does the use of scenarios affect the quality of decision-making when assessing trade-offs during early-stage design activities*?

2 THEORETICAL BACKGROUND

2.1 Technology development, technology assessment and trade-offs

In the context of this research, technology is defined as "the theoretical and practical knowledge, skills, and artifacts that can be used to develop products and services as well as their production and delivery systems" (Burgelman *et al.*, 2009). Therefore, technology development is the process resulting in "new knowledge, new technology, a technical capability, or a technological platform" (Cooper, 2006). It often takes place during the front-end of innovation or at the same time as an early-stage product development (Aristodemou *et al.*, 2019; Brilhuis-Meijer *et al.*, 2016).

During the technology development process, companies periodically evaluate the progress of the technology, in an activity called technology assessment. Originally employed in policy impact analysis, technology assessment was adopted by private corporations to evaluate the potential benefits (e.g., profits and risks), of new technological options (Rip, 2015). While there is no standardized methodology for technology assessment, commonly used methods include cost-benefit analysis, roadmapping, and surveying (Tran and Daim, 2008). The decision criteria used are often linked to business-related measures and the financial promise of the technology, such as strategic alignment, market attractiveness,

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and net present value (Mitchell *et al.*, 2022). However, private and public entities involved in technology development are increasingly including sustainability and circular economy concerns among their decision criteria (Cluzel *et al.*, 2016; Olivier *et al.*, 2021). Methods used in sustainability-focused technology assessment include carbon footprint, simplified life cycle assessment, eco-design tools, and checklists (Villamil *et al.*, 2022). The addition of new criteria to support decision-making inevitably led to the occurrence of design trade-offs, i.e. conflicts between these criteria.

2.2 Foresight, future scenarios, and decision-making

Given the very uncertain and prospective nature of technology assessment, foresight methods have been proposed - and widely used - to stimulate futures thinking in assessment activities (van der Duin, 2016). Foresight methods focused on exploring possible futures include roadmapping, trend analysis, scenarios, and backcasting (Neuhoff *et al.*, 2022). Scenario planning, specifically, is used by companies as a tool to reflect upon plausible and relevant futures, leading to new insights. Created in the 1960's and defined in the 1980's, scenario planning is widely used in corporate settings with varying degrees of intentionality and structure (van der Duin, 2016). There are several methods that can be used to build scenarios, from judgement and intuition to more structured approaches such as systems modelling (Bishop *et al.*, 2007). Scenario planning has been applied to design (Candy and Dunagan, 2017) and business decision-making (Doualle *et al.*, 2019).
As illustrated by the "futures cone" (Figure 1), scenario planning can support the technology development process by generating a range of possible outcomes. Scenarios foster reflection and systems thinking, including considerations on the sustainability of possible applications of a technology. In fact, scenarios have been linked to a raise in credibility of decision-making, by reducing epistemological uncertainties and addressing bounded rationality (Chermack, 2004; Spielmann *et al.*, 2005). In sustainability assessments, scenarios have been used with simplified life cycle assessment, showing promising results (Bisinella *et al.*, 2021; Cucurachi *et al.*, 2018; Delpierre *et al.*, 2021).

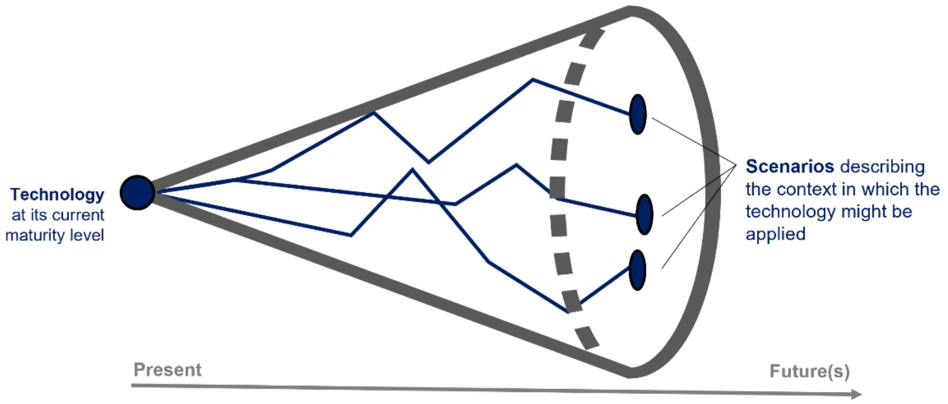

Figure 1. The future possibilities cone and scenarios, stemming from a technology being developed. Adapted from Gall et al. (2022).

3 RESEARCH METHODS

3.1 Study design

The study followed a quasi-experimental approach with a pretest-posttest non-equivalent control group design (Campbell and Stanley, 1963). This empirical research design measures the effect of an intervention (e.g., medical procedure, vaccine, behavioural change, or, in the case of this research, the presence of scenarios for technology assessment) in both a control and an experimental group, in two moments in time. The two groups are then compared, and differential improvement/deterioration between the groups can, in general, be attributed to the intervention (Miller *et al.*, 2020)
The quasi-experimental approach manages to avoid threats to internal validity which are common in other usual empirical designs, such as case studies or one-group designs (Campbell and Stanley, 1963). However, its main drawback stems from selection bias - the intervention and control groups can have pre-existing differences which could also explain the observed effect. Therefore, control and intervention groups need to be chosen carefully as to be as similar as possible (Miller *et al.*, 2020).

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The experimental setup adopted in this research is illustrated in Figure 2. First, participants in the control and intervention groups were shown two mechatronic concepts in the context of a technology development project and asked to choose the best one, based on their own criteria, with a 10-minute time-limit (Task 1). The concepts were described in a feasibility report which showed financial and environmental impact information. No other information about the concepts, the company, the users, or other factors, was supplied. After making their decision, the participants were asked to complete a questionnaire (Questionnaire 1). Then, participants in the control group were shown two new mechatronic product concepts, and again asked to make a decision between them in 10 minutes or less (Task 2a). The reports shown to the control group had the same information as the one they had previously seen, with updated data to reflect the two new concepts. Meanwhile in the intervention group, participants were shown reports which contained information about two future scenarios for each concept, in addition to the baseline (Task 2b). Finally, participants in both groups were invited to answer the questionnaire once more (Questionnaire 2).

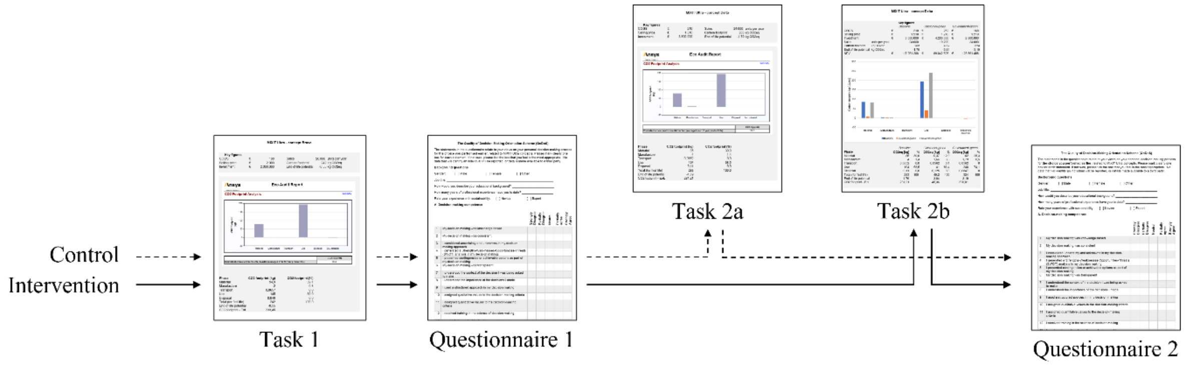

Figure 2. Experimental set-up – a pretest-posttest non-equivalent control group design.

The feasibility reports presented for Tasks 1 and 2 were developed by the authors to portray trade-offs (i.e., conflicts between criteria), including business and environmental sustainability metrics. The financial and business information represented in the reports are cost of goods sold (COGS), one-off investment, number of units sold per year, selling price, and net-present value (NPV). The environmental figures were generated using the Ansys Granta EcoAudit software, focused on carbon footprint (Ashby *et al.*, 2021). The scenarios used to elaborate Task 2b were developed by the researchers before the quasi-experiment, following the scenario-cross method (van der Giesen *et al.*, 2020). The complete description of the scenarios and scenario-cross can be found in the supplementary material at doi.org/10.11583/DTU.21564744.

3.2 Data collection instrument

The questionnaires to measure changes in quality of decision-making (Questionnaires 1-2) were developed based on a generic instrument for assessing the quality of decision making in companies, developed and validated by Donelan et al. (2016), which demonstrated relevance and reliability in different organisational contexts (Bujar *et al.*, 2019). The Quality of Decision-Making Orientation Scheme (QoDoS) consists of 47 statements with Likert-scale response options divided in two-parts, namely (i) organisational approach and culture and (ii) individual competence and style. For this study, only individual decision-making characteristics were investigated, therefore the first part of the questionnaire was not applied. Eight questions related to the decision history and general behaviour of the participants were excluded, as they proved to be confusing for respondents in early tests of the experiment and meaningless in the context of the experiment. Table 1 compiles the 16 QoDoS statements included in the final questionnaire. An additional open-ended question was added, relating to the approach of the participant when presented with a trade-off.

Data collected through the questionnaires was entered into Microsoft Excel, where the QoDoS items were scored from 0 to 4 following a Likert-scale, from "strongly disagree" (0) to "strongly agree" (4). The change in scores from the pre-test (Task 1) to the post-test (Task 2) was evaluated per participant. Then, the mean was taken across participants, to establish the mean change for each QoDoS item. Subsequently, the results were aggregated according to the Quality of Decision-Making Practices (QDMP), as shown in Table 2. QDMP are ten best-practices in decision-making, first elaborated for the pharmaceutical industry (Bujar et al., 2022), but that are also applicable in other industrial settings. After calculating the scores per participant in each test, the change in QDMP scores was computed by subtracting pre-test scores from post-test scores, and finally the mean was taken across participants for both groups. Due to the adapted questionnaire for this study, some of the QDMP were not applicable (NA), as discriminated in Table 2.

Table 1. QoDoS statements included in the questionnaire.

Item	Keyword	Statement
1	Knowledge	My decision making was knowledge based
2	Consistent	My decision making was consistent
3	Uncertainty	I considered uncertainty and unknowns in my decision-making approach
4	SWOT	I generated a SWOT analysis in my decision making
5	Contingency	I presented contingencies or achievable options as part of my decision making
6	Transparent	My decision making was transparent
7	Context	I understood the context of the decision I was being asked to make
8	Importance	I understood the importance of the decisions I made
9	Structured	I used a structured approach in my decision making
10	Qualitative	I assigned qualitative values to the decision-making criteria
11	Quantitative	I assigned quantitative values to the decision-making criteria
12	Training	I received training in the science of decision making
13	Intuition	I used intuition or “gut-feeling” in my decision making
14	Emotion	Emotion was part of my decision making
15	Slow	I experienced “paralysis by analysis” caused by my slow decision making
16	Relative	My decision making was improved by assigning relative importance to criteria

*Table 2. QDMP and their relation to QoDoS items. Items followed by * indicate unfavourable practices, where the Likert-scale was reversed.*

QDMP Shortname	QDMP	QoDoS items
Structure	Have a systematic, structured approach to aid decision-making	1, 2, 4, 7, 9, 12, 13*, 15*
Roles	Assign clear roles and responsibilities	*NA*
Criteria	Assign values and relative importance to decision criteria	10, 11, 16
Bias	Evaluate both internal and external influences/biases	14*
Alternatives	Examine alternative solutions	5
Uncertainty	Consider uncertainty	3
New information	Re-evaluate as new information becomes available	*NA*
Impact	Perform impact analysis of the decision	8
Transparency	Ensure transparency and provide a record trail	6
Communication	Effectively communicate the basis of the decision	*NA*

A double-tailed Welch's t-test was employed to statistically analyse the difference between each group's mean change in score. Different than a standard t-test, Welch's t-test accounts for samples with different sizes and variances. The probability associated with a t-test is called the p-value. Usually, if the p-value is lower than 0.05, there is strong evidence that the means of the samples are statistically different. In this case, we could say the intervention had a statistically significant effect in QoDoS and QDMP scores.

3.3 Study participants

Two sessions following the same experimental design were held. The first session was performed with 11 employees of a manufacturing company, hereafter referred to as "experts". The participants were engineers, designers, and project managers, ranging from 5 to 30-plus years of professional experience. Workshops were conducted individually with each employee, in which all steps show in

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Figure 2 were completed. Participants were pre-defined into control (n=5) or intervention (n=6) groups according to their position and sustainability proficiency, to have a balanced representation of the company profile in each group. The second session was carried out with engineering students enrolled on a sustainable design course at the Technical University of Denmark, in one workshop. The students, mostly second-year undergraduates, were randomly assigned to control (n=14) and intervention (n=22) groups. Introduction and analysis steps were performed with free communication between members of the same group, but the questionnaires were answered individually.

4 RESULTS AND DISCUSSION

4.1 Overall results across the observed groups

The results show a relative improvement in 6 out of the 7 tested Quality of Decision-Making Practices (QDMP) in the intervention group (Figure 3). Participants who were shown scenarios had, in average, higher scores in "Structure", "Criteria", "Biases", "Uncertainty", "Impact" and "Transparency". The only decrease can be seen in the "Alternatives" practice.

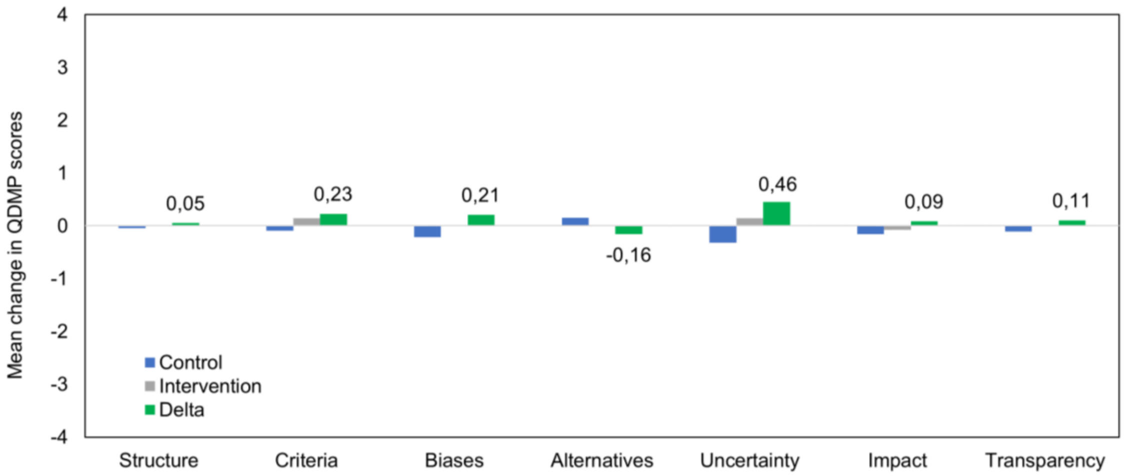

Figure 3. Mean change in QDMP scores for all participants and delta between groups.

Experts (i.e., company representatives) showed more extreme results compared to novices (i.e., students) - see Figure 4. Data from experts provides evidence that scenarios can improve the quality of the following decision-making practices: "Structure", "Criteria", "Biases", "Uncertainty", and "Transparency". Students had only minor improvements in "Uncertainty" and "Impact".

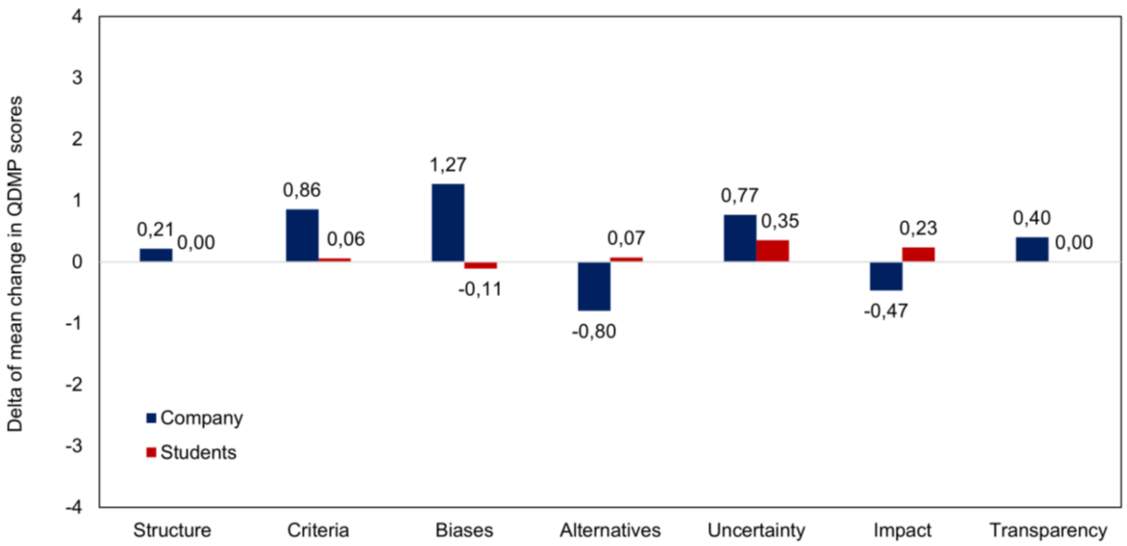

Figure 4. Delta of mean change in QDMP, comparing experts and students.

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The decrease seen for experts in "Impact" and "Alternatives" could be explained by their "ill-behaviour", as stated by Cross (2004): expert designers may have a higher confidence in their own judgment and, because of their experience in a certain domain, tend to hastily move on from the problem definition stage. Consequently, experts may impose a specific view of the problem onto the analysis and quickly get attached to early concepts or alternatives, failing to explore more alternatives or evaluate the impact of their design decisions. In those cases, having additional information provided to them in the form of scenarios could interfere with the experts' preferred behaviour. Similar reasoning can be applied to their decrease in "Impact", as scenarios push decision-makers to consider other possibilities and, in that way, may compete with the experts' usual conduct of imposing their own problem framing. In brief, while scenarios may disrupt the experts' "ill-behaviour", the same cannot be stated for novices, which are not used to these types of assessments and do not have pre-defined ways of framing the problem. In that sense, scenarios may help them to grasp the impacts and uncertainty related to the task at hand. This is substantiated by previous research, as Burleson et al. (2021) show that support for gathering qualitative context information related to design tasks can be particularly useful for novices, and less so for experts. Therefore, scenarios (which are shown to have their greatest impact in context-understanding) may be especially helpful for novices.

The complete results, for both QDMP and individual questionnaire items (including mean change and standard deviation (SD), delta of mean change between groups, and Welch's t-test probability (p-value)) are shown in Table 3. It is important to notice that the effect size across all QDMP categories is small. Specially in "Impact", "Biases", and "Transparency", the intervention group did not show improvements with the scenarios, but rather showed no (or less) decrease as compared to the control group. Moreover, no practice or item reached the usual significant level of p-value <0.05, meaning that we cannot strictly state that any of the effects are statistically significant. QoDoS items 7 ("Context") and 10 ("Qualitative") are close to reaching the significance limit, at p-values of 0.06. The two items (shown in italics in Table 3) can be interpreted as having the largest statistical significance. The full results and raw data can be accessed in the supplementary material at doi.org/10.11583/DTU.21564744.

Table 3. QDMP and QoDoS items results

		No scenarios		With scenarios			
		Mean	**SD**	**Mean**	**SD**	**Delta**	**p-value**
QDMP	Structure	-0.04	0.40	0.01	0.55	0.05	0.929
	Criteria	-0.09	0.53	0.14	0.94	0.23	0.383
	Biases	-0.21	1.27	0.00	1.05	0.21	0.858
	Alternatives	0.16	0.96	0.00	1.09	-0.16	0.788
	Uncertainty	-0.32	1.20	0.14	1.11	0.46	0.375
	Impact	-0.16	0.60	-0.07	0.94	0.09	0.778
	Transparency	-0.11	0.94	0.00	0.94	0.11	1.000
QoDoS item	1 (Knowledge)	-0.26	0.87	-0.07	0.81	0.19	0.220
	2 (Consistent)	-0.37	1.30	-0.21	0.88	0.15	0.826
	3 (Uncertainty)	-0.32	1.20	0.14	1.11	0.46	0.375
	4 (SWOT)	0.37	1.12	0.11	1.07	-0.26	0.393
	5 (Contingecy)	0.16	0.96	0.00	1.09	-0.16	0.788
	6 (Transparent)	-0.11	0.94	0.00	0.94	0.11	1.000
	7 (Context)	*-0.42*	*0.84*	*0.11*	*1.31*	*0.53*	*0.063*
	8 (Importance)	-0.16	0.60	-0.07	0.94	0.09	0.778
	9 (Structured)	0.26	0.87	0.00	1.36	-0.26	0.404
	10 (Qualitative)	*-0.16*	*0.69*	*0.18*	*1.31*	*0.34*	*0.064*
	11 (Quantitative)	-0.11	0.99	0.32	1.39	0.43	0.508
	12 (Training)	0.21	0.79	-0.14	0.89	-0.35	0.326
	13 (Intuition)	0.11	0.94	0.39	1.20	0.29	0.386
	14 (Emotion)	-0.21	1.27	0.00	1.05	0.21	0.858
	15 (Slow)	-0.21	1.47	0.00	1.15	0.21	0.745
	16 (Relative)	0.00	0.75	-0.07	1.21	-0.07	0.657

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4.2 Discussion: the influence of scenarios for decision-making

The results presented in this study are initial evidence that scenarios contribute to the decision-makers' awareness of context, biases, and uncertainty in early-design tasks. Although no item strictly reached statistical significance, this does not prove that the effect is absent. In small samples, the size of an effect must be large for the p-value to reach the significance threshold (Amrhein *et al.*, 2019). In this study, with a relatively small sample size and small effect sizes, a positive effect can be interpreted as (initial) evidence for the intervention, even with p-values slightly above the significance threshold.

Considering the most statistically significant result (QoDoS item 7, "Context"), scenarios increased participants' reflection on the context of the decision. In a technology assessment setting, this means that scenarios could be used by decision-makers as way of incorporating epistemological uncertainty in their analysis and increasing awareness of the socio-technical context surrounding the technology, including aspects that potentially influence its social and environmental impacts. These results corroborate previous work on how scenarios may increase the metacognition of actors engaged in decision-making (Harries, 2003). The use of scenarios might encourage awareness of one's own process of making decisions, as well as the context in which the decision is being made. This reasoning is also shown by Chermack (2004) and Doualle et al. (2019), who explain that groups can benefit from scenarios by building a shared representation (i.e., mental model) of the decision context, increasing the quality of decision-making. The qualitative feedback collected from participants provides additional evidence that the intervention group expanded their consideration for hidden assumptions as well as potential risks or benefits of the concepts. The same phenomenon can be observed in QoDoS item 3 ("Uncertainty"), which showed a marked improvement when scenarios were present.

Scenario planning theory indicates that some of its benefits may come from the process of building scenarios. Chermack (2004) points out that scenario building may help in facilitating the transfer of information along an organization, which was not measured in this study. However, many of the benefits of scenario building were still detected in the experiment (i.e., understanding the decision context, consideration for uncertainty and bias), even though participants did not partake in the scenario creation and discussion itself and were only shown its outcomes. This is a first step in showing that some benefits of scenario planning stem from simply making the information available to decision-makers.

The results also demonstrate that scenarios led to participants having a more intuitive approach, in addition to identifying relevant values and criteria for the decision. Statement 10 ("Qualitative") of the questionnaire suggests that scenarios induced participants to use more qualitative values in their decision-making, demonstrating a better understanding of the important criteria at play. By choosing qualitative values for the different criteria, participants indicated a better grasp of which information on the report mattered in the given context. The same reasoning is applied by Bodin et al. (2016), which highlight how scenarios can positively influence decision-making style to be more "intuitive" by allowing decision-makers to "get better at piecing together available information" and to "gain insight and awareness about how their choices might play out" in the future. This is further corroborated by the qualitative feedback in this study, as some participants stated that the decision-making process became less clear, relying more on assumptions and having a qualitative approach. Therefore, decision-makers in TD projects can use scenarios with the purpose of having a broader view on what (qualitative) criteria and values should be considered given the context. This can be especially important when it comes to assessing the sustainability of a technology, a complex and broad subject.

Moreover, the results show that scenarios might hamper the consideration for alternative solutions, although the effect is small. This could be explained by the increased effort demanded from the participants in the intervention group, which received a more complex task, while having the same time as the other group. The time-restriction and increased complexity may have stopped participants from considering alternative solutions to the problem and led them towards a more intuitive response. These effects could be mitigated by providing a more straight-forward visualisation of scenarios, in a way that is easily understandable and that reduces effort required from decision-makers.

5 CONCLUSION

This study is, to the extent of the authors' knowledge, the first to empirically demonstrate how scenarios have the potential to increase the quality of decision-making when assessing trade-offs during early-stage design activities, including sustainability assessment of technologies. The results provide initial evidence that scenarios may positively influence decision-makers in two key factors,

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- **Context**: increase in awareness of context, biases, uncertainties, hidden assumptions, and potential impacts - this is especially important for sustainability assessment in technology development settings, where context (i.e., epistemological) uncertainty is apparent.
- **Criteria**: enhanced use of clear qualitative criteria and values for decision-making. Having clear criteria is key when evaluating sustainability, a very broad and complex subject.

However, the uptake in intuitive reasoning led to a weaker consideration of other alternative solutions, possibly due to time limitations and increased effort required. The study also shows that expert designers respond differently than novices when faced with scenarios and decisions involving trade-offs.

This study and its methodological design have some limitations. The low number of participants (n=47) weakens the power of the results presented here and does not allow for statistically significant findings. Therefore, the obtained results should be used as an illustration of the possible effect of scenarios in decision-making, and as a first step in quantifying its effects. Furthermore, a non-equivalent control group design, especially in the company settings, is prone to selection bias. Finally, participants in both sessions were mostly from the same cultural background, which could lead to skewed results, and hampers the generalizability of the findings.

Future research should focus on new rounds of the experiment, with higher number of participants and stronger randomization for achieving a more statistically powerful result. Similarly, having participants actively become involved in the scenario planning process, as well as allowing participants to have more time to get familiar with the technology or to perform the tasks, could further support and strengthen the findings presented here. Finally, a more well-suited data instrument could be developed to better capture the decision-making aspects present in design activities.

In summary, having awareness of the decision context and clear decision criteria are valuable assets when assessing technologies and trade-offs, particularly in sustainability assessment. Thus, design methods and tools aiming to support decision-making in these settings should incorporate aspects of future scenarios, as scenarios tends to produce higher quality decisions.

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