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Forming Digital Sustainable Product Development Support

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Abstract

Sustainability has shifted from strategically important to business critical for several manufacturing industries. This paper introduces an implementation framework to increase the capabilities in companies to design, develop and offer sustainable product- and production solutions in line with new regulatory strategies and plans.

Based on a questionnaire survey, conducted in ten different product development companies representing different industrial sectors, the status and needs of sustainable product development were captured. Further on, a better understanding of the capabilities for a forthcoming digital sustainable product development support, were identified in an action research-based approach with three industrial companies.

This paper presents the rational of a digital sustainable product development support, in relation to global sustainability goals and societal dimensions of sustainability transitions. The main results from the questionnaire presents the challenges and needs of capabilities for product developers and design engineers to develop more sustainable solutions in a resource efficient way. The action-based research with the three industrial manufacturing partners resulted in a set of common key activities and detailed requirements for a digital sustainable product development support. Finally, the paper describes a first prototype of a digital platform, i.e. Digital Sustainability Implementation Package-DSIP, and discusses future work.

Keywords: sustainable design, digital design, systems engineering (SE), early design phase, design support system

1 Introduction

The incentives for new and sustainable solutions continuously increase. Manufacturers need to simultaneously make radical technology shifts and develop business arrangements on a disruptive market. Until recently, sustainability has predominately been addressed using analysis-oriented Design for Environment methods and tools, such as Life Cycle Assessment (LCA), and designing to meet Legislative Compliance. Furthermore, most larger companies have established environmental reporting as a key function on a company level. Sustainability, however, requires a systemic approach. The UN SDGs address a wide range of aspects that together represent society´s global sustainability challenges. In response, circular economy has become a strong trend the latest years and set the focus on transforming business to maximise re-use of material. Sustainable design will be influenced by the megatrends digitalization and circular economy (Brahma, 2021). A similar conclusion is drawn in Hallstedt et al. (2021), who concluded that digitalisation, sustainability, and servitisation are intertwined areas, and that circular economy in combination with digitalisation is a key to realize Product Service System solutions and to meet society's challenges and stakeholders' sustainability requirements in terms of resource savings and more efficient usage of products.

The role of designers is expected to change from design of artefacts to design of entire solutions (see e.g., Isaksson et al., 2009). This implies that designers need to consider the behaviour of products and solutions and their impact over complete life cycles (Ramani et al, 2010; Carlsson et al, 2021), developed and organized by business networks together with several suppliers and other partners with different capabilities (Hallstedt et al. 2021).

Our research objective is to increase the capabilities in companies to design, develop and offer sustainable product- and production solutions in line with new regulatory strategies and plans, e.g. strategies for circular economy, new EU taxonomy, upcoming Digital Product Passport legislation (EC, 2020; Lucarelli et al. 2020). The goal with this research is therefore together with software solution providers, and industrial partners build a digital platform to demonstrate and validate capabilities that will enable industries to better develop and provide sustainable products and circular solutions to the market. Based on this, the main challenge we want to address in this paper is how to empower engineers and design teams to model, present, evaluate and develop solutions in a time-limited environment, and to make prioritized decisions towards the most resource-efficient and sustainable solution.

2 What does a sustainable design and development support package need to address?

One main societal challenge is the limited time to make the transition towards a more sustainable society (IPCC, 2022). Industries need clearer incentives from authorities and support in their design processes to make this shift happen sooner rather than later. The profound socio- ecological impacts of products and technologies spurs many industries towards sustainable innovation. However, lack of decision-support in the design process hinders companies to realize this.

Applied design research can contribute to reach the UN SDGs, such as SDG 9 'Industry, Innovation, and Infrastructure', and, SDG 12, "Responsible consumption and production", although it is important to highlight that all SDGs are interconnected and hence will be affected by each other. For instance, a sustainable solution cannot be achieved by few innovative products alone, but requires a system shift in how products are manufactured and used (Bengtsson et al. (2018). In the same way, innovation benefits from increased diversity and gender balance, SDG 5. Unless the lack of decision-support is resolved, SDG 8 "Decent work and economic growth" cannot be met. Overall, SDG 9 contributes to a system shift in innovation as it calls for drastic change in how companies operate to fulfil their role in the transition towards a sustainable society. A particular difficulty is the systemic nature of sustainable development, where clear and powerful metrics, such as focusing on reducing, or eliminating CO_2, can also result in unwanted effects that negatively impact other sustainability factors (Bengtsson et al. (2018).

There are challenges at different societal dimensions that all need to be addressed from a system perspective. Five societal dimensions of sustainability transitions are described in previous research by Miedzinski et al. (2019): i) technologies, products, and processes; ii) business models; iii) infrastructure and production systems; iv) regulatory framework; and v) cultures and values. Each of the different dimensions has challenges related to sustainable product development, which represent the rational for the development of Digital Sustainability Implementation Package (DSIP), Figure 1.

i) Technologies, products, and processes: The meaning and interpretation of sustainability varies within companies, partially due to lack of common and shared understanding (Schulte & Hallstedt, 2017; Sakao & Brambila-Macias, 2018). Making right decisions when developing sustainable product and solutions is therefore a challenge. Decisions made early in the innovation process, where guidance for sustainable design is limited, have a major impact on the product lifecycle including its production and resource flows (Ramani et al, 2010; Diaz et al, 2021; Poudelet et al, 2012). There is therefore a need to integrate sustainability aspects early to guide decisions rather than late assessments after detailed design.

The DSIP solution need to enable companies to increase their competence in sustainable product development and in product modelling and evaluation, meaning that sustainability can be taken into consideration in the early product design stages and considered together with functional requirements. DSIP shall also provide support to develop a customized engineering working bench with an efficient data management system to be able to create a design space that also includes product- and service solutions meeting the needs of a circular society. By increased capabilities in strategic, tactical and operational levels, companies can steer towards innovative sustainable and circular solutions rather than only incremental improvements.

ii) Business models: A recent report from UN EIT Climate KIC (Pamlin, 2020) shows that while industrial companies have a key role in taking necessary actions in steering society into a sustainable and circular direction, there is a challenge today to develop and launch the necessary, disruptive innovations and new business models. The transformation requires capabilities and support on several organizational levels, i.e. strategic, tactical and operational, for a development of new and disruptive business models and innovations to happen.

The suggested DSIP need to provide novel support tools for companies to e.g., assess portfolio and risk aspects from a short-term business perspective to a long-term strategic perspective (Villamil et al., 2021; Schulte & Knuts, 2022). Based on these assessments, long-term plans and new business models can be developed for disruptive sustainable innovations.

iii) Infrastructure and production systems: Lack of standardized approaches for sustainability data sharing and management hinders development of value chains for circular solutions (Melander, 2017). Digital solutions are not yet developed to support value chain collaboration which enable efficient resource usage throughout the product life cycle.

The suggested DSIP needs to increase the competitive advantage of companies, in any type of sector, by leveraging the industrial digital infrastructure to accelerate sustainable product-, service-, and production systems development. Thus, using DSIP should encourage resource efficiency through practices such as industrial symbiosis for remanufacturing. Since manufacturers develop and produce products based on product definitions, sustainable characteristics need to be associated with product information.

iv) Regulatory framework: Today, authorities struggle to incentivize disruptive and sustainable innovations. Proactive companies seek to be ahead of regulations but also in line with expectations at the market, which makes them competitive. Authorities and standardization organizations must hence, in a faster pace, increase their capabilities to encourage companies to lead a sustainability transition through measure and control mechanisms.

The suggested DSIP needs to provide support for authorities to validate the sustainability performance of products. For instance, a new suggested measurement approach, can complement e.g., life cycle assessments, to ensure compliance with current and coming policy initiatives, such as the EU Green Deal. DSIP's tool-kit and digital platform solution will provide guidance and support for ISO standards, e.g. ISO/TC 323 Circular Economy (EC, 2020).

v) Culture and Values: Manufacturing companies need to convince the younger generation that industry is not just causing sustainability problems but rather can be active leaders in the transition towards sustainability by launching disruptive innovations. Otherwise, industry will face difficulties in attracting young and well-educated employees (Willard, 2012). Therefore, a key factor for companies is to invest in new capabilities to create sustainable solutions.

The proposed DSIP thus needs to initiate behavioral changes internally at different organizational levels, and externally among customers, suppliers, and partners across value chains. Thereby, it can have effects beyond its users and spread to a variety of companies internationally. With increased capabilities in companies, sustainable solutions will be developed that meet the expectations of the younger generation, and the demand from society, for companies to make the necessary transformation to a sustainable society.

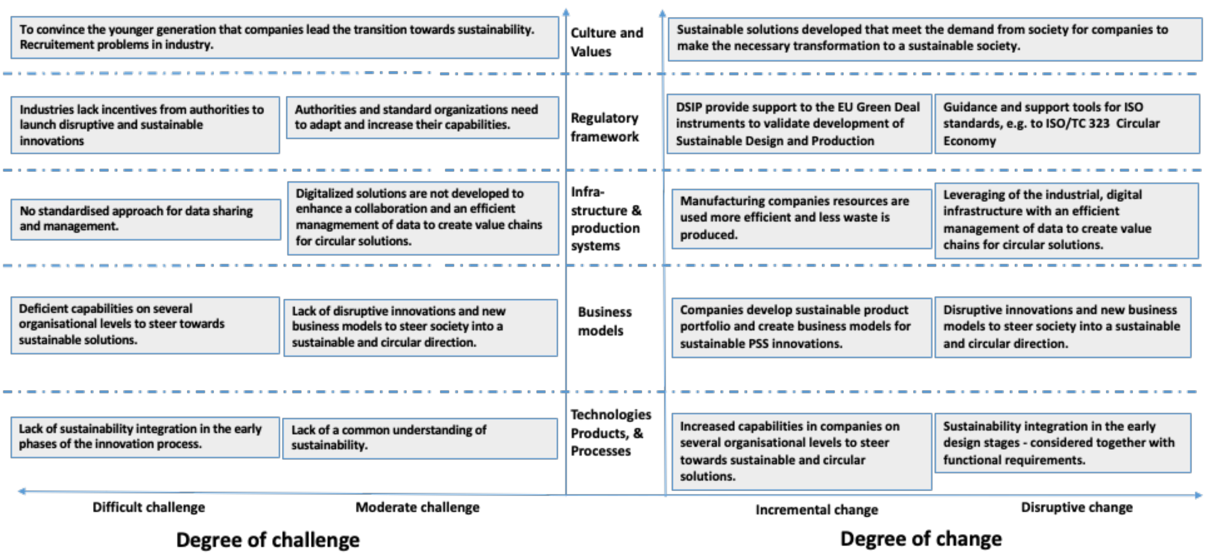

Figure 1. Challenges at different societal dimensions and expected changes at different societal dimensions addressed by Digital Sustainability Implementation Package- DSIP.

In summary, a consistent support package for sustainable product development needs to respond to multiple aspects of importance from a sustainability perspective, including its role to facilitate change and industrial transformation.

3 A survey to identify the capabilities needed to develop more sustainable solutions

In Hallstedt et al., (2020) it is concluded that there is a need for change in product design capabilities as a consequence of the three mega-trends, i.e. sustainability, digitalization and servitization, for individual engineers to master the increased complexity and its interaction with its use context. A survey was therefore recently conducted with the purpose to learn of the current status and perceived support for today's sustainable product development, and identify the needs for DSIP.

The survey was sent out to ten different product development companies representing different industrial sectors, both business to business, and business to consumers, with different types of solutions, such as jet engine components, transport solutions, easy-to-assemble furniture, kitchen appliances and home accessories, consultancy services within product development and production, construction machines, sealing solutions for cable and pipe penetrations. The questionnaire was structured in seven different themes with a total of 22 questions, see Table 1.

The questionnaire was answered by 87 people, in which a majority, 55 percent, do product development. The profile of the respondents was 95% male and 62% had more than 20 years' work experience. The key results from the survey for each capability theme were as follows:

Business benefits and risks of sustainable and circular solutions
A clear majority of the respondents (91%) consider it important to be able to offer sustainable solutions by 2030. However, circular solutions are not necessarily the same thing as sustainable solutions (Pieroni et al., 2019). This view was evident by most as 57% of the respondents consider it equally urgent as for other industry sectors, to adapt to circular business models by 2030. See Figure 2.

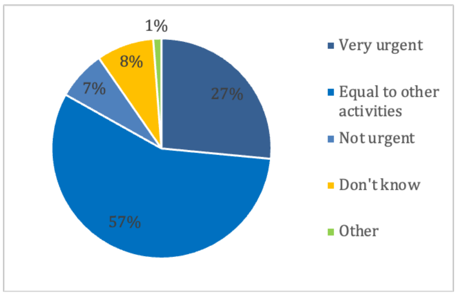

Figure 2. The urgency of that industry adapts to circular business models compared to other industries.

Measure sustainability in early phases
To adapt and develop sustainable solutions have some barriers, as for example it is hard to know if the proposed solutions are more sustainable or not. A majority (74%) of the respondents do not currently use (or do not know of) any measurement approaches to indicate the sustainability profile of solutions in early phases. In general, the respondents lack effective support to identify, model and assess sustainability today. However, the respondents could see many benefits with understanding and defining the sustainability performance, such as: i) creating awareness of sustainability consequences for different solutions; ii) avoiding negative sustainability consequences; iii) defining sustainability requirements, iv) finding a way for how to view sustainability as a driver for innovation, v) providing value to the company, vi) including sustainability alongside other parameters in requirement setting, before concept selection. The challenges to be able to define the sustainability performance were: i) what is meant by 'sustainable', i.e., having a clear picture of the target, ii) difficulties to trace performance over time, iii) different markets having diverse needs, and regulations, standards, and certifications, which can be a barrier to change.

Table 1. Excerpt of survey questions to investigating the current state, challenges and needs in product development companies in relation to certain capability themes.

Identify, define, model and evaluate design concepts

Capability themes	Questions
Business benefits and risks of sustainable and circular solutions	• Does your company currently use a systematic approach to identify business benefits and risks for sustainable and circular solutions? • How would you rate your product development teams' understanding of the conditions needed to speed up the organization's contribution to a sustainability transformation? • How important is it that your company can offer sustainable solutions by 2030?
Measure sustainability in early phases	• Do you currently use any measurement approaches to indicate the sustainability profile of your solutions in the early phases of the product innovation process? • If yes, what measurement approach(es) do you use? • What could be the benefits of being able to understand and define the sustainability performance for design solution early in the innovation process?
Identify, define, model and evaluate design concepts	• When considering alternative solutions (product concepts), how do you consider sustainability characteristics of these concepts? • What modelling support do you use to represent concepts (e.g. office documents, CAD, PLM).
Assess business impact and value trade-off support	• What decision support do you use to evaluate design alternatives and decide about design trade-offs (e.g., increasing product performances vs. reducing product cost)? • Can you tell us a trade-off anecdote (a "story" from a product development project), where sustainability concerns were down-prioritized against other dimension (e.g., cost, product performance)?
Implementation of Sustainable Product Development	• What support tools, that you know of, can be used to improve sustainability performance of new design solutions? Please share examples with tool name, and if you want, experiences. • To what degree do you perceive the following aspects to be challenging for implementing sustainable product development? Please feel free to comment, add other challenge/s, and elaborate with examples.
Sustainability data management	• Do you currently have any process to identify and trace data that impact on sustainability profile of your solutions during their life cycle? (i.e. consistent data management from the early phases of the product innovation process until end of life) If yes, what approach do you use? • If yes, please elaborate how widely the product data management approach is used across various products (volume) and through the value chain (width and depth)?
Format of DSIP as business offer	• What format of DSIP solutions may a design and manufacturing company pay for?' (e.g. toolbox, methods, consultancy services, software applications)

The common tools to support modelling of concept representations were CAD/PLM, but there was no defined tool to support sustainability considerations, see Figure 3. Some respondents however suggested and use pre-defined sustainability criteria and indices, as well as project-specific demands, as a lens to consider the sustainability performance of alternative solutions. The CAD and PLM tools are used to represent the critical information of products, and it is expected that product information also can represent necessary information for the product's sustainable behavior.

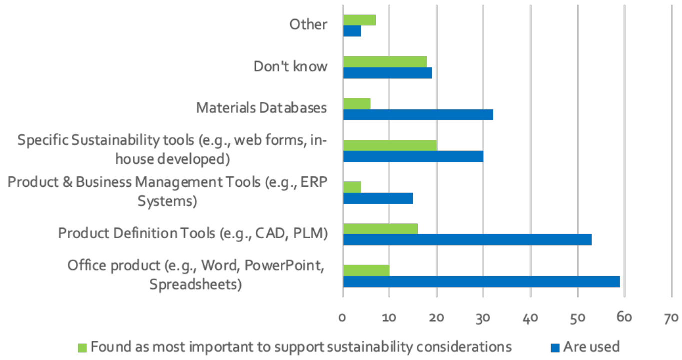

Figure 3. Support tools to identify, define and evaluate design concepts.

Assess business impact and value trade-off support

Sustainability is still considered as a cost by many. *"...In general, you always must settle for an acceptable level of cost for sustainability since you always could do more." (One of the respondents)*. However, there seemed to be a trend among the participants that the view of sustainability is shifting from a cost- to a value- focus and play an increasing role from a business perspective. Therefore, it becomes more important in trade-off situations to identify the sustainability requirements that go beyond the legislative compliance.

Implementation of Sustainable Product Development

The survey showed that the main challenges for sustainable product development implementation in the studied companies are: i) lack of knowledge of available tools, ii) lack of support tools, iii) difficult to make sustainability tangible, and iv) difficult to measure sustainability. Other challenges were: lack of customer demand; limitation of time resource; commitment from management; government regulations that are not adaptive enough: lack of tangible and general parameters; and, lack of clear roadmap to sustainability.

The knowledge and access to the most suitable support tools was one of the barriers to successfully implement sustainable product development, even if a few (about 20 respondents) mentioned that they use tools such as, LCA, an eco-calculator, or a company specific sustainability impact assessment. It was suggested by the respondents to increase the knowledge of the support tools, and make them easy to use to increase the applicability of support tools. Policies, regulations, and standards were listed as a measure to increase the usage of the support tools. Preferably also be able to use standardized, credible, and reliable tools, and data. Clear business incentives, customer requirements, commitment from management, and tools that are adapted to the specific company were other incentives that can increase the usage of support tools for an implementation of sustainable product development.

Sustainability data management

When it comes to sustainability data management, 54% of the respondents do not know if they currently have any process to identify and trace data that impact the sustainability profile of their solutions during the complete life cycle. 30% state that they do not have any process for this, and only 12% of respondents knew that they used specific data management standard, e.g. ISO 10303. Among those companies that trace data, it is used in forecasting to improve product efficiency. Generally, there were limited experiences from managing sustainability data in the product innovation process. One reason can be that it is difficult to know what sustainability data is or constitute of. Another, that sustainability is down-prioritized or there is low willingness of collaboration between different actors in the value-chain and therefore they do not have focus on sustainability data management.

Format of DSIP as business offer
A majority of the respondents thought that a forthcoming DSIP solution should preferably be offered as a consultancy service, a software application provider, as a method support, and/or as part in education and training. See Figure 4.

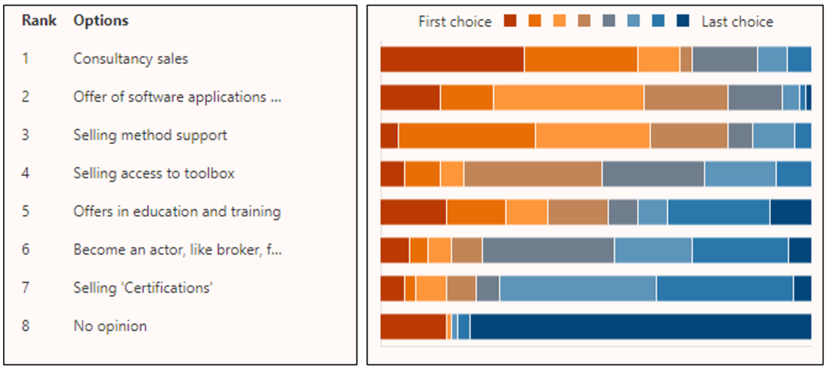

Figure 4. Preferred format of DSIP as business offer.

In summary, the survey clarified both gaps perceived in current practice and raised expectations on the forthcoming DSIP support. An interim observation is that the awareness and understanding of sustainability aspects in product development varies in the companies, and systematic and systems support are not well established.

4 A generic sustainable design framework- based on industrial use cases

A high-level summary of the industrial needs, paving the way to understanding the capabilities of the forthcoming DSIP, were identified in an action research-based approach with three industrial companies.

	Sustainability criteria	**Sustainable design alternatives**	**Impact based evaluation**	**Sustainable product management**
Societal and market expectations and needs	Understand sustainability context, needs and conditions	Assess feasibility of concept alternatives	Quantify impact of solutions	Adapt to changes in conditions or provided solutions
Manufacturer and/or solution provider	Define requirements and criteria	Search and define sustainable solutions		
Supplier and enabler of sustainable aspect	Link criteria to solutions available and offered	Provision of alternative enabling solutions	Provide information that enable impact assessment	Offer new, adapted, or reuse of solution elements
Sustainable Product Lifecycle Management	Representation, search and retrieval of sustainability criteria connected with the product- and solution lifecycle information			

Figure 5. Key activities for integrating sustainability in product development.

The figure above, Figure 5, displays a generic view on key activities and detailed requirements in the product development logic, and the vertical dimension represents first the "value chain" view plus highlighting the sustainable product lifecycle management perspective.
The first challenge is the difficulty to represent a sufficiently complete and balanced set of criteria used to search for solutions and later evaluate and validate the solutions fulfilment and impact. Therefore, one of the key activities is to define the "sustainability criteria" which goes along with the product innovation process of a company where the requirement development and objectives are set. The solution elements, provided by the suppliers of material and services,

also need to fulfil the sustainability criteria. If a high-level expectation is to make use of re-used material, the supplier needs to provide information of the origin of the material. The sustainability criteria need further to be representable in a Product Lifecycle Management (PLM) environment.
The second key activity is to search for and represent alternative solutions to the targeted design space. Sustainable solutions are likely to come with additional requirements, such as circular solutions, rather than products defined primarily with the objective of being manufacturable. From Product-Service System development literature, its known that manufacturing industries need to replace a "Design to manufacture" view to a "Design to sustain" view, which also challenge the way such products, or solutions, are represented (Isaksson et al., 2009). The solutions tie the product close to the business concept in a value chain.
The third key activity is to understand the sustainability impact of proposed solutions, and to include life cycle parameters into design. The challenge is the ability to make value and risk-based decisions to realise the proposed solutions, typically trading sustainability impact with other factors of importance.
The final fourth activity is to maintain functionality of the product. Once the product, or solution, has been realised and in use, it needs to be maintained.

5 A digital package for sustainable design

Based on the survey results and previous research findings (Hallstedt et al., 2020), a digital knowledge platform, including a toolbox and a toolguide, was developed with the purpose to support an implementation of sustainable product development in industry.

In this first DSIP prototype, the toolbox contains support tools that are selected from the research in sustainable product development and system engineering design to meet the following requirements:

- **identify** and **formulate** sustainability indices
- **measure** expected sustainability impacts
- **design and evaluate** sustainable solutions
- **improve** decision-making on strategic- tactical and/or operational organizational levels
- **guide** product developers with prerequisites to innovate sustainable products and circular solutions.

The task was to bring a heterogenous set of tools and methods together, allowing individual adaption and compliance with industrial environments and tools. Therefore, a first DSIP prototype was developed with categorized and detailed information of the decision support tools, that gave the structure of a tool-guide and a database of the tools.

The result is an excel template with a structure of some basic information from each tool and categories that differentiate the tools, which are used for sorting and filtering of the tools in a DSIP tool-guide. See Figure 6, excerpts of tools and an example of how tools are displayed in the DSIP toolbox.

A central idea is for product developers in industry to easier get access to information needed during product development based on the needs of the user. In the case that the user is new to sustainable development, the focus is to gain basic knowledge and awareness of what role the tools have, in what way sustainability factors can be addressed etc. This drives the user friendliness of a tool solution and an educational view. For more advanced user, the focus is to access and understand specific tools that matches a particular situation. For such users, the needs are more specific, and the information of each tool needs to be more precise. Finally, the DSIP toolkit need to be adaptable and expandable, as more tools are likely to be added and when companies want to integrate the toolkit with its existing IT infrastructure and tools.

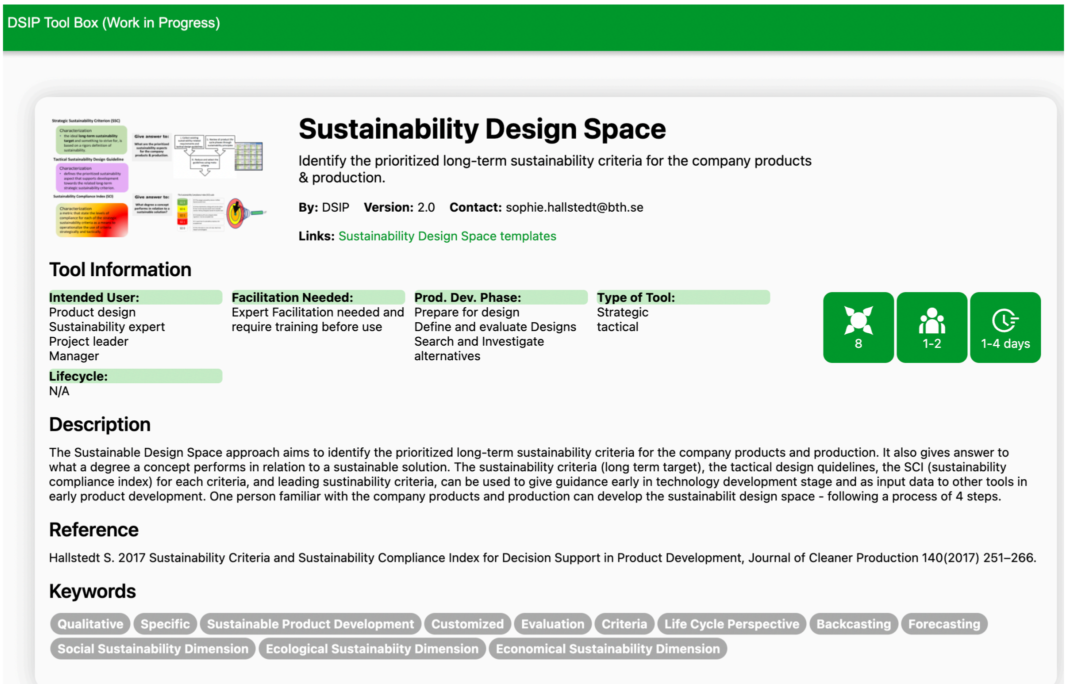

Figure 6. An example of how tools are displayed in the DSIP toolbox.

6 Concluding Discussion and future work

Further work with developing DSIP is in progress. In general terms it is concluded that it meets several needs such as:

- Align strategic decision making across different organization levels: Decision makers on all organisational levels require capabilities that empower them to implement a sustainability perspective in their processes. Engineers on an operational level request easy access to sustainability data to compare operational impact of alternative strategies, technologies and product concepts.
- An accessible packaged set of tools for sustainable product development: Tools should in a user-friendly way present and visualise data to support communication and decision-making. Current tools and data availability do not satisfy these needs.
- Trace and associate the product definition with sustainability data and criteria: New legislation and market needs, forces manufacturers to identify and trace relevant sustainability product data. This requires new capabilities, methods, and processes to utilize digitalization for sustainable innovations.

What makes the DSIP solution unique is not only the set of newly developed and accessible, science-based decision-support tools, but also the data management solution that makes the data to, from and between these tools securely managed, traced, and made available. The strategic objective is to investigate to what extent current standards for Product Life Cycle Information Management, such as ISO 10303-239 can provide support for the activities and solutions that needs to be managed from a sustainability perspective. The DSIP solution also uses a commercially available information management system to demonstrate and evaluate information management aspects of DSIP solutions in the industrial use cases. The importance of attending to the information management perspectives when introducing new, digital support tools for design and development cannot be underestimated (Geiricke et al., 2020). Today industries already manage their information in existing IT systems and have established tool-support for their current product development. Therefore, any new support will need to fit with an already existing support system.

In further research, several things need to be addressed to mature and expand the use of the DSIP toolbox. First, the provided methods and tools have to a main extent only been validated in isolation, and that is not enough for them to be used in conjunction (Gericke et al, 2020). It has been observed in other contexts that using methods and tools in conjunction can cause unprecedented issues related to the information and data management if not considered appropriately (Mallalieu et al. 2022). Therefore there is a need to test and investigate how the provided tools can be integrated and used in conjunction. Second, the DSIP solution aims to increase the utilisation and industrialisation of methods and tools by making them accessible for industry. This puts further requirements on how the methods and tools are provided along with what information is associated with them. The industrialisation of engineering methods has long been an observed issue and it is important that the user understands how to use the method and its purpose (Eder 1998; Araujo et al., 2007). One computerized Morphological Matrix tool called Morpheus (Martinsson et al. (2022) is provided by the DSIP, and it has previously demonstrated cases where the tool is misunderstood and misused in university courses. There is thus a need to validate that the current method- and tool-specific information provided by DSIP is sufficient to ensure intended use. Third, the DSIP consist of a tool guide which aims to help practitioners identify and choose the method or tool most suited for their specific issue. This function is currently based on questions that are linked to characteristics of tools. There is an ambition that the DSIP tool guide will make use of ratings and evaluations of the tools, which could potentially improve this functionality further, and base the suggested tools on previous outcomes. This feature needs to be developed and validated.

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