INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED23
24-28 JULY 2023, BORDEAUX, FRANCE

DERIVE AND INTEGRATE SUSTAINABILITY CRITERIA IN DESIGN SPACE EXPLORATION OF ADDITIVE MANUFACTURED COMPONENTS

Mallalieu, Adam (1);
Martinsson Bonde, Julian (1);
Watz, Matilda (2);
Wallin Nylander, Johanna (3);
Hallstedt, Sophie I. (2);
Isaksson, Ola (1)

1: Chalmers University of Technology;
2: Blekinge Institute of Technology;
3: GKN Aerospace

ABSTRACT

Additive manufacturing has the potential to decrease the climate impact of aviation by providing more light-weight designs. Sustainability is however required to be assessed from a systemic view, including all lifecycle phases, and from a social, ecologic, and economic dimension. This is however challenging in early phase design, where also a large design space need to be explored. A case study is carried out with an aerospace company where two candidate engineering design tools are combined to address this. The integration of these two engineering tools are applied on a Turbine Rear Structure, and shows promising results in enabling a systemic view of sustainability to be integrated and assessed in early phase design space explorations of additive manufactured components. It is recommended that the integration between the two tools is further established and validated.

Keywords: Sustainability, Design methods, Additive Manufacturing, Digital Design Experiments, Sustainability Criteria

Contact:
Mallalieu, Adam Mattias
Chalmers University of Technology
Sweden
adammal@chalmers.se

Cite this article: Mallalieu, A., Martinsson Bonde, J., Watz, M., Wallin Nylander, J., Hallstedt, S. I., Isaksson, O. (2023) ‘Derive and Integrate Sustainability Criteria in Design Space Exploration of Additive Manufactured Components’, in *Proceedings of the International Conference on Engineering Design (ICED23),* Bordeaux, France, 24-28 July 2023. DOI:10.1017/pds.2023.120

1 INTRODUCTION

The aviation industry needs to evaluate new solutions and designs to meet the challenges of the ongoing climate crisis (ACARE, 2022). New technologies and materials such as, composite materials, hydrogen combustion, and additive manufacturing need to be developed and implemented to accelerate the transition towards a more sustainable society. The manufacturing technology, Additive Manufacturing (AM), can potentially enable more light-weight designs due to its capability to build complex geometries (Dordlofva et al., 2016). However, designing products or Product-Service Systems (PSS), with improved sustainability performance does not only consider characteristics of the physical artefact, but also the services and material-flows provided along the value chain. Therefore, design solutions need to be assessed from a full life-cycle perspective including all three dimensions of sustainability, i.e., ecological, social, and economic, to determine the sustainability performance of a design (Carlsson et al, 2021; Ramani et al., 2010). AM has been shown to provide sustainability advantages but also challenges, and of different kind throughout the AM value chain (Ford et al., 2016; Villamil et al., 2018). Furthermore, while AM enables the manufacturing of complex geometries, it comes with its own set of constraints. This puts further pressure on the early phases of design, where the decisions made will heavily impact the manufacturability of the final product (Taguchi et al., 1990). To mitigate such issues, manufacturability evaluation can be included as part of design space exploration (Martinsson Bonde et al., 2022). AM involves decision making in different design domains which requires the ability to identify and manage trade-offs between different design objectives, and some approaches that have been proposed to account for this are e.g., Bertoni et al. (2020); Borgue et al. (2020); Liu et al. (2021). The identification of relevant and effective sustainability criteria that enables a comparison with sustainability and other design objectives therefore becomes a critical task for organisations that want to conduct sustainable product development (Nilsson et al., 2018). A recent study Hallstedt et al., 2022 found that quantifying sustainability and enabling assessment with other design objectives with digital design support is lacking in industry. Altogether, this calls for research that investigates the opportunities to develop design support that enables engineers to explore the design space of additive manufactured components while applying a systemic sustainability perspective. Adding to previous research on integration approaches enabling quantitative assessment of sustainability criteria based on design parameters, e.g., Kwok et al. (2020), this research aims to address the following research question:

> *How can a systemic view of sustainability be integrated and assessed in early phase design space explorations of additive manufactured components?*

2 RESEARCH APPROACH

This paper is based on a case study from an industrial use case of a large first-tier supplier of integrated metallic and composite assemblies for aero-structures and aero-engine products. This case study is part of a larger research project called DSIP (Digital Sustainability Implementation Package), see Hallstedt et al. (2022). The project includes a large consortium of industrial actors, service providers, and researchers. The project objective is to enable industrial actors in adopting a strategic sustainability perspective in the early product innovation process. DSIP compiles novel digital support tools to develop more sustainable and circular solutions, which is a prerequisite for sustainable resource management and use of technologies. The project aims to support industry in developing more sustainable solutions by making engineering design tools for Sustainable Product Development (SPD) and Value Driven Design (VDD), accessible to industry. In this paper, we adopt the definition of a tool provided by Gericke et al. (2017): “An object, artefact or software that is used to perform some action (e.g., to produce new design information). Tools might be based on particular methods, guidelines, processes or approaches or can be generic environments that can be used in conjunction with many methods”. The research approach applied in this study utilises a stepwise approach for breaking down a complex high-level challenge into concrete capability needs (i.e., design support tools). The approach consisted of six main steps: i) Use Case Formulation; ii) Scenario Breakdown; iii) Generating an Idealised Design Process; iv) Capability Need Identification; v) Capability Matching; vi) Execution. This research approach required close collaboration with the industrial use case company as the research team identify answers to all steps together with the industrial team. The researchers act as facilitators and poses guiding questions to the industrial team, whereas they later verify the outcome of each step before entering the next. This process is further described in the section below.

2.1 Applying the stepwise approach on an aerospace company

The industrial use case company were initially asked to provide a high-level challenge or problem, and overall design context in the **first step (Use Case Formulation),** the following was formulated by the case company: “Our aim is to learn more about the sustainability impact of these technologies (additive manufacturing) and their different design parameters. We need to explore the sustainability perspective of these technologies (circularity, data gathering/handling, sustainable decision-making during design, evaluation compared to traditional manufacturing processes).” The AM technologies that are referred to here are Laser Powder Bed Fusion (LPBF) and Laser Metal Deposition (LMD).

The **second step (Scenario Breakdown)** was to break down the overall need into more specific needs or problems. This resulted in two different and more distinct industrial use case scenarios. The one addressed in this paper is *Design for sustainability with AM (LPBF)* where the company identified four more concrete needs compared to the high level challenge formulated in step one: i) How can the company take circularity and sustainability into account during concept selection and design of a new product? ii) How can the company generate sustainable concepts with limited data/knowledge/information on what is more sustainable? iii) How can the company handle design trade-offs? iv) How can the company optimise AM for sustainability?

In addition to the more concrete needs, a case component was also chosen in this step. The industrial use case company chose a Turbine Rear Structure (TRS) (see Figure 1) as the case component. The TRS is an aero-engine component installed behind the turbine stages. The function of this component is to guide turbine gas flow, transfer mechanical load from shaft to aircraft mount. The thermo-mechanical operative, and cyclic, loads limit useful life. So called off-design loads, such as unbalance loads in the case of lost fan blade drive design. Thus, when evaluating TRS designs it is important to evaluate the stiffness and buckling resilience of the structure. The TRS is manufactured as a single casting, or by fabrication of sub-components. AM can be used to print both full size components and sub-components. In this paper, it will be assumed that the TRS is printed using LPBF.

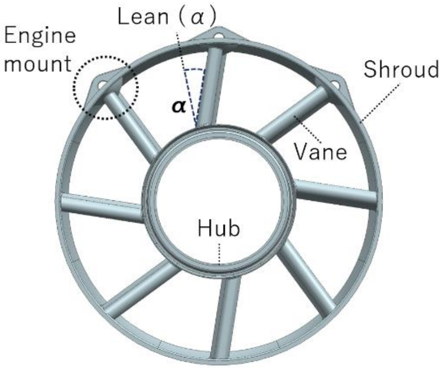


Figure 1. A 3D-model of a TRS, seen from the front

The **third step (Generating an Idealised Design Process)** was to understand the design context of the case company, i.e., the typical design activities conducted by the company in the industrial use case scenario. The first activity of the identified idealised design process was *Identification of Sustainability Criteria*, which corresponds to the identification of relevant sustainability criteria for the TRS. The second activity was *Analyse Sustainability Criteria*, which corresponds to analysing the identified sustainability criteria further e.g., formulate targets and/or indicators. The third activity was *Generate Design Concepts* which corresponds to exploring different design alternatives e.g., materials and/or geometries. The last activity was *Evaluate Design Option/Identify Trade-Offs* with respect to the identified sustainability criteria and other design objectives such as stiffness. This would then support decision of whether to use AM or not. The idealised process is illustrated by the blue boxes in Figure 2. The inputs and outputs of the design activities are denoted by letters A-E, and the actual data- and information flow of these is described in detail in Section 4. The idealised design process is visualised in Figure 2.

The **fourth step (Capability Need Identification)** meant the industrial use case company were to identify the capability needs they have for each design activity. The identified capability needs are illustrated by the white boxes in Figure 2, and the arrows indicate where in the process. It should be noted that there were additional needs identified, but only the ones addressed in this study are included in the figure.

The **fifth step (Capability Matching)** included the capability need to be matched with a capability, i.e., engineering design tools. Two design support tools, which are part of the developed and accessible tools in the DSIP project, were identified and proposed as candidates to address these capability needs. These two tools are *Leading Sustainability Criteria Workshop Approach* (LEASA) which is a Sustainable Product Development tool and *Digital Design Experiments* (DDE) which is a Value Driven Design tool. LEASA aims to address capability needs 1-3, and the combined output of LEASA and the DDE aims to address needs 4-5. The two proposed tools are explained more in detail in Section 3.

The **sixth step (Execution)** was the actual application of the two engineering design tools (involving the industrial use case company) on the TRS, and it is presented in Section 4.

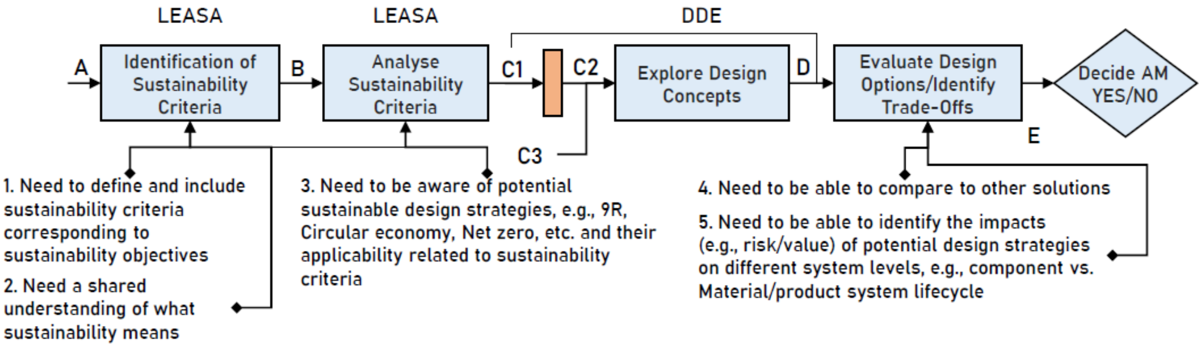


Figure 2. Idealised design process (blue boxes) with identified capability needs numbered 1-5. Letter A-E are the in-/outputs. LEASA and DDE are acronyms for the design tools applied

3 BACKGROUND OF THE APPLIED ENGINEERING DESIGN TOOLS

Two already developed Sustainable Product Development and Value Driven Design engineering design tools are applied in this paper and they address different capability needs. They are used in conjunction since they together form a candidate choice for addressing the combined set of needs identified by the case company. This section provides a brief background and explanation to the two tools such that the reader easily can follow the rationale behind the choice of applying these tools.

3.1 Leading sustainability criteria workshop approach

Leading sustainability criteria (LSC), i.e., criteria with indicators effectively guide concept development within contextually relevant sustainability constraints, i.e., a “sustainability design space” (Hallstedt, 2017). To identify sustainability criteria using systems thinking and all sustainability dimensions is critical, as up to 80 percent of a product-based solutions’ lifecycle sustainability impact is determined during the earliest stages of concept development. Previous research on sustainability criteria and indicators within design and product development has identified some necessary characteristics that such sustainability criteria should have to be applicable in product design. For instance, sustainable design criteria should not be solution-dependent, be measurable and verifiable with accessible information, and represent all sustainability dimensions (Schmidt et al., 2006). Several, but not all, of the sustainable design criteria and indicator-characteristics can be found among preferred requirement characteristics emphasised within traditional requirements engineering (Walden et al., 2015): i) Implementation independent, to specify what a design should do, but not how it should be done; ii) Necessary, i.e., there should not be requirement combinations which signalise that not all requirements are needed to specify what a design should do or provide; iii) Feasible, meaning that the requirement should be possible to meet, e.g., from a risk-, budget-, time-, and technology perspective; iv) Singular, i.e., include only one function or constraint, v) Unambiguous, i.e., be formulated to avoid different interpretations; vi) Verifiable, using a single method such as an inspection, an analysis, a demonstration, or a test.

A need to support companies in developing so called “leading sustainability criteria” has been identified in several, research studies together with manufacturing industry (Kravchenko et al., 2019; Watz and Hallstedt, 2022). To ensure that developed LSC are identified using a strategic sustainability lifecycle perspective while meeting characteristics of both sustainability design criteria and design requirements, Watz et al. (2021) proposed a set of LSC characteristics which can be used as a checklist in requirements development. Altogether, LSC; i) Address aspects that are complicated/expensive to change later in the product development process; ii) Cover all lifecycle stages; iii) Address all sustainability dimensions; iv) Be defined in a measurable way. A workshop-based method using templates with guiding questions was therefore developed to support the development of LSC in early phase design projects. The workshop-based method, so called the Leading Sustainability Criteria Workshop Approach (LEASA) helps users to fulfil this checklist and is inspired by two SPD methods, i.e., SPD workshop method (Schulte et al., 2018) and Sustainability Design Space (Hallstedt, 2017). LEASA is a series of workshops and focus group discussions facilitated by a sustainable product development expert, i.e., a researcher or a practitioner. The different steps apply a combination of back casting, simplified lifecycle assessment, gap analysis and creative prototyping framed by requirements engineering through the integration of the above-mentioned checklist. As such, the expert first facilitates a workshop with a transdisciplinary company team to i) prototype ideal characteristics of a sustainable solution and to ii) identify sustainability hotspots that the company sees today, and finally to iii) brainstorm design strategies that could bridge from the current state to the ideal scenario. Thereafter follows iterative expert work and focus group sessions with, e.g., representatives from key company functions such as sustainability, regulatory compliance, design, and sourcing, supported by the LSC-checklist and workshop templates. In this way, the initial workshop findings are consolidated, interpreted, and continuously matured into a list of LSC. The workshop templates help capture thorough descriptions to provide a basis for continued requirement development, which should explain why the LSC are critical to address in early phase, as well as enable measurement and assessment. Thus, the template offer space for; describing what the LSC is about, the rationale behind the LSC, including references to internal and external stakeholder expectations, as well as for proposing suitable indicators and target values.

3.2 Digital design experiments

In this paper “Digital Design Experiments” (DDE) is a short-hand reference to experiments run using a set of software tools used in combination with each other to generate and evaluate designs. This tool kit thus includes geometry generation software, and analysis scripts that interface with e.g., Ansys and Siemens NX through their Application Programming Interfaces (APIs) to run various kinds of analysis. Additionally, these softwares have been designed to enable these processes to be run automatically, enabling the exploration of large design spaces with manual intervention. Information between processes, and result files are typically stored as Comma-Separated Value-files (CSV).

The digital design experiments consist of four steps: i) generation of the Design of Experiments; ii) generation of the context models; iii) analysis of the context models; iv) results aggregation. To generate the Design of Experiments the boundaries of a set of key design variables was defined. These boundaries were then used to configure a hypercube Design of Experiments, used to sample 100 different design points. The Design of Experiments was used as an input to a geometry generation software, which creates geometries using Siemens NX API (NXOpen). A more detailed description of the geometry generation process can be found in a separate paper (Martinsson Bonde et al., 2022). Three types of context models were created: i) a CAD part geometry, ii) a finite element mesh, and iii) an STL-geometry (STL-files are a commonly used format to relay geometry data to e.g., AM slicing softwares). These context models were then applied in each of their corresponding analysis processes. The CAD Part was used to extract the volume of each design point using the Application Programming Interface (API) of Siemens NX. The mesh was used to perform a stiffness and buckling analysis with Ansys Workbench. The load-cases used for this analysis were based on a subset of load-cases used at the aerospace company together with available material data. A novel addition to the DDE in this study, is that the STL-geometry was used to calculate the support volume. This addition enables evaluation and trade-off studies with both structural performance and AM manufacturability. AM manufacturability is evaluated through calculating the support volume, which contains the structures necessary for supporting the print and dissipating heat. These support structures are removed in post-processing and need to be minimised to reduce waste. The volume required by these support structures is approximated by evaluating polygon-faces in the STL-file that do not comply with the minimum overhang angle requirements and calculating the necessary volume of the structure needed to support such faces. The results were aggregated into a single CSV-sheet, which was used to visualise and analyse the results.

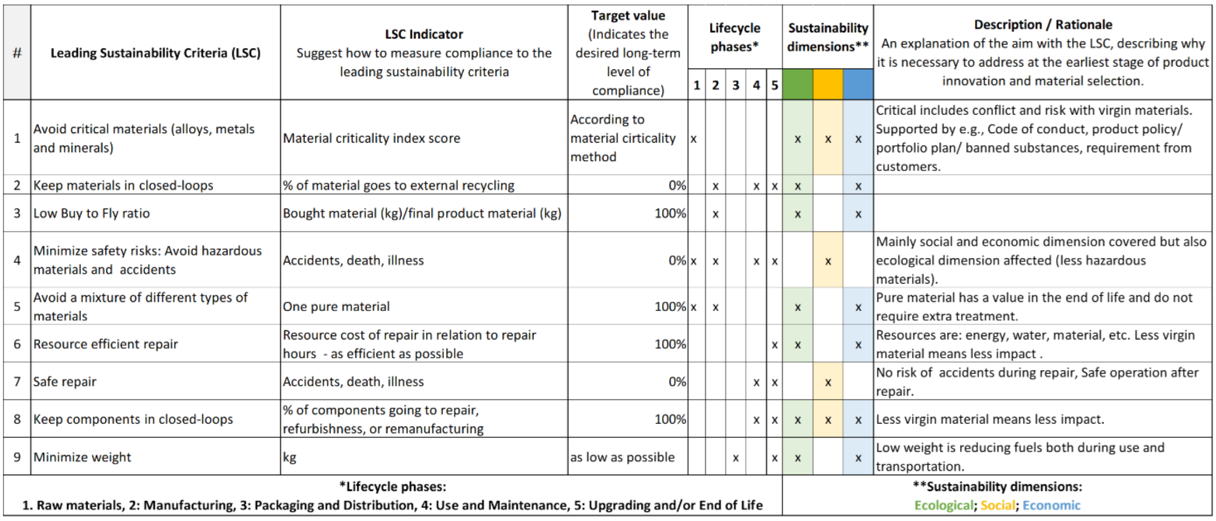
4 RESULTS: APPLYING LEASA AND DDE IN CONJUNCTION

This section presents the results of applying the two engineering design tools on the TRS and follows the logic in Figure 2. The letters A-E will be used when referring to the inputs and outputs from each design activity.

4.1 Identification of sustainability criteria and analysis of criteria using LEASA

Applying the LEASA workshop method on the TRS correspond to the inputs and outputs, A-C1, in Figure 2, and resulted in nine LSC (C1). The LEASA workshops were facilitated by a research team (design researchers and sustainable product development researchers) and engaged a purposely sampled multi-disciplinary team from the case company, representing e.g., engineering design, risk management, regulatory compliance, sourcing, sustainability, and business development, in two workshops. The in-going information (A) was a description of the case, i.e., the TRS, the workshop templates, and company documentation, e.g., policies, guidelines, and material lists. The first workshop was organised online where the company participants discussed and answered guiding questions which were captured in the workshop templates by the researchers resulting in output B. The findings were thereafter consolidated and refined by the researchers, and then iterated (B) with a smaller case company group in a second workshop. Thereafter, a final set of LSC was defined resulting in output C1. The final output (C1), i.e., the LSC are presented in an excerpt of the final workshop template, see Table 1. For more information and examples of features of the LEASA workshop method, e.g., guiding questions, see Watz et al. (2021).

Table 1. Leading sustainability criteria for the TRS



#	Leading Sustainability Criteria (LSC)	**LSC Indicator** Suggest how to measure compliance to the leading sustainability criteria	**Target value** (Indicates the desired long-term level of compliance)	**Lifecycle phases***					**Sustainability dimensions****			**Description / Rationale** An explanation of the aim with the LSC, describing why it is necessary to address at the earliest stage of product innovation and material selection.
				1	**2**	**3**	**4**	**5**	🟩	🟨	🟦	
1	Avoid critical materials (alloys, metals and minerals)	Material criticality index score	According to material circicality method	x					x	x	x	Critical includes conflict and risk with virgin materials. Supported by e.g., Code of conduct, product policy/ portfolio plan/ banned substances, requirement from customers.
2	Keep materials in closed-loops	% of material goes to external recycling	0%		x		x	x	x		x	
3	Low Buy to Fly ratio	Bought material (kg)/final product material (kg)	100%		x				x		x	
4	Minimize safety risks: Avoid hazardous materials and accidents	Accidents, death, illness	0%	x	x		x	x		x		Mainly social and economic dimension covered but also ecological dimension affected (less hazardous materials).
5	Avoid a mixture of different types of materials	One pure material	100%	x	x				x		x	Pure material has a value in the end of life and do not require extra treatment.
6	Resource efficient repair	Resource cost of repair in relation to repair hours - as efficient as possible	100%					x	x		x	Resources are: energy, water, material, etc. Less virgin material means less impact .
7	Safe repair	Accidents, death, illness	0%				x	x		x		No risk of accidents during repair, Safe operation after repair.
8	Keep components in closed-loops	% of components going to repair, refurbishness, or remanufacturing	100%				x	x	x	x	x	Less virgin material means less impact.
9	Minimize weight	kg	as low as possible			x		x	x		x	Low weight is reducing fuels both during use and transportation.
***Lifecycle phases:** **1. Raw materials, 2: Manufacturing, 3: Packaging and Distribution, 4: Use and Maintenance, 5: Upgrading and/or End of Life**									****Sustainability dimensions:** **Ecological; Social; Economic**			

The table lists information about which lifecycle phases and sustainability dimension a criterion addresses, suggests indicators to measure compliance with a criterion, and provide a short description that motivates why a criterion was defined. The actual template also provide space to add references to internal and external motivators (e.g., company policy and/or guidelines, and/or regulatory frameworks, or industry standards). Such information was however not included in this case, but instead listed in the "Description column". As Table 1 illustrates, the criteria address all life cycle stages, all sustainability dimensions, are provided with a measurable indicator, and are identified as critical to decide upon in early phase design to avoid locking in negative sustainability impacts.

4.2 Additional step of integrating the LSC into the DDE

LEASA and the DDE have not been developed and tested in conjunction prior to this case study, and this made it interesting to check if any of the LSC from the previous step could be directly assessed in the DDE. This step is marked as an orange block in Figure 2. where output C1 from LEASA, see Table 1, i.e., LSC indicators, are transformed into input C2, through logical relationships between C1, C3 and/or D. For example, different geometries (volumes) are part of output D and makes it possible to assess the LSC *Minimize weight*. It is assumed that the different geometries generated in the DDE would have the same density. The volume can be transformed into weight using material density as input C3 if more than one material was considered in the DDE. *Minimize weight* was initially the only LSC that was possible to assess using the DDE in its current set-up. However, as mentioned in Section 3 a novel addition was made to the DDE in this study, where the volume of the support structure could be estimated. This made it possible to assess the LSC *Low Buy-to-Fly ratio*, which is treated by the company as **'weight in'** compared to **'weight out'**, and is approximated using the expression $\eta = D_{esign}/(D_{esign} + S_{upport})$, where η is the buy-to-fly ratio. It should also be noted that volume instead of weight is used to assess the *Low Buy-to-Fly ratio*. It is here assumed that non-printed material i.e., powder, is either reused or recycled by the case company.

4.3 Explore design concepts using DDE

Different design concepts of the TRS are explored using DDE, where 10 different geometrical design parameters are varied in the DDE, see Figure 3.

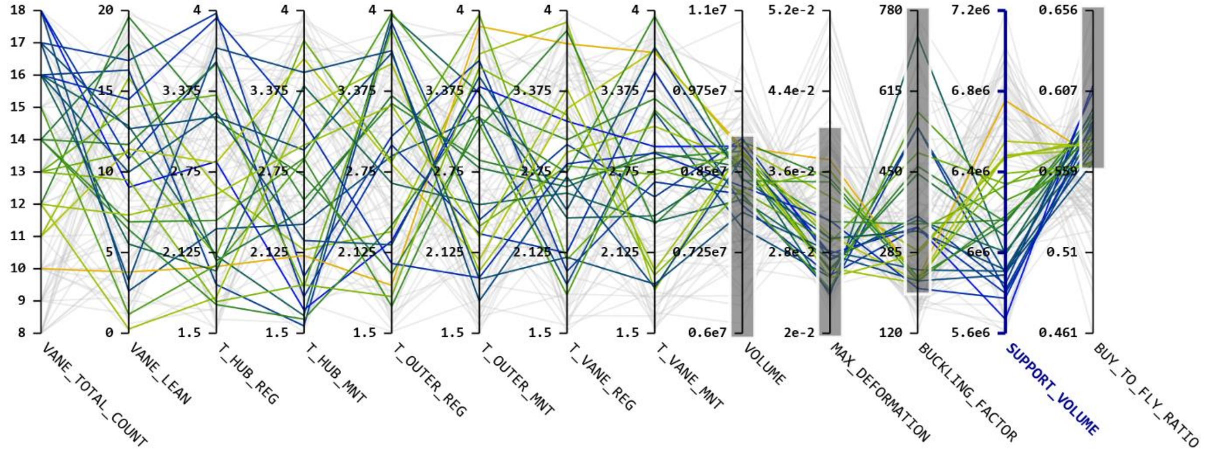


Figure 3. Parallel coordinates plot depicting the inputs and outputs of the digital experiments

A limitation for this design exploration was that only one material (Inconel 718) was included, due to lack of available and appropriate material data. It is however possible and recommended to include more than one material if appropriate material data is available. The DDE requires additional data and information such as load cases and UDFs, which differ from what is generated and used in the upstream design activities and is therefore denoted as C3. The DDE generates output D which is illustrated in Figure 3. This output is used together with output C1 to evaluate the design options and identify trade-offs and is further described in the section below.

4.4 Evaluate design options/identify trade-offs using LEASA and DDE

This design activity is based on company-contextual and sensitive information, such as how the LSC are weighted against other criteria. We will therefore only showcase how such an analysis can be done using parts of the output from LEASA and DDE. The results of the DDE were aggregated and visualised in a parallel coordinates diagram, as presented in Figure 3. In this diagram, each line represents a specific design point. Superimposed on top of the data are also filters based on discipline-specific requirements. These filters exclude any design points that are not light enough, stiff enough, or resource efficient enough in manufacturing. From the results a few take-aways can be deduced: i) A high vane count is typically beneficial for meeting the criteria; ii) A higher thickness on the shroud walls is required to maintain an acceptable stiffness, even though this increases the volume/weight of the structure; iii) The buy-to-fly ratios of the remaining design points are quite far from the ideal value of 1, which prompts the consideration of whether the design can be further adapted for AM.

As mentioned earlier, the DDE conducted in this paper was only used to directly assess two of the nine LSC (LSC3 and LSC9). Many of the other LSC can be assessed through a more qualitative approach, e.g., Sustainability Fingerprint (Hallstedt et al., 2023). Further described, **LSC 1** *Avoid critical materials (alloys, metals, and minerals)* can be treated as true OR false, and the value of including it in a DDE would be increased if more than one material is considered. There is no real trade-off for this case study since only one material, Inconel 718, was included in the design exploration. Inconel 718 can be assessed by the company internally, by e.g., using a material criticality method (Hallstedt and Isaksson, 2017) to decide whether the design is acceptable (i.e., true, OR false). **LSC 2** *Keep materials in closed-loops* and **8** *Keep components in closed-loops* target more circular resource flows and are more dependent on the value chain of the TRS rather than the geometry of the TRS. LSC 2 is more impacted by the contracted powder-suppliers, and LSC 8 is impacted by the contracts to customers and/or end users. Furthermore, different materials could affect the contracted supplier's ability to recirculate powder, and the ability to keep TRS in closed loops. These LSC can therefore be used to qualitatively to assess different materials explored in the DDE, meaning that the value of including these criteria would increase if more than one material was included in the DDE. **LSC 3** *Low-Buy-to Fly ratio* and **LSC 9** *Minimize weight* can be assessed directly by the DDE, and two examples were presented in the take-aways above. **LSC 4** *Minimize safety risks: Avoid hazardous materials and accidents* and **5** *Avoid a mixture of different types of materials* are also difficult to assess directly using the DDE since only one material is considered in this case study. It would however be possible to assess these in a similar way as for LSC 2 and 8 when more than one material is part of the design exploration. **LSC 6** *Resource efficient repair* is not directly integrated into the DDE. One way to assess this LSC using DDE would be to assess the accessibility of commonly damaged surfaces of the TRS. This has been demonstrated before by Al Handawi et al. (2020). A similar addition to the DDE can potentially be used to support the assessment of LSC 6 since an additively manufactured TRS would be repaired using blown powder directed energy deposition, where the nozzle needs to have access to the damaged surface of the TRS. Lastly, **LSC 7** *Safe repair*, is difficult to be assessed directly in the DDE, since it relates to how the repair of the TRS is carried out downstream in the lifecycle, e.g., safety equipment and procedures. The criteria could also be used to qualitatively assess different materials.

5 DISCUSSION AND CONCLUSION

The aim of this paper was to investigate how a full systemic view of sustainability can be integrated and assessed in early phase design explorations of additive manufactured components. A stepwise approach is used for breaking down a complex high-level challenge into concrete capability needs. This leads to the identification of two candidate engineering tools in LEASA and DDE which are combined to address this, and it is discussed below.

The findings from this case study show that there are opportunities for integrating sustainability criteria for additive manufactured components in early phase design explorations. This is done by combining the two tools in LEASA and DDE. However, it is not as simple as applying these tools in sequence. The use of these in combination required an additional time-adding step where the output of LEASA were analysed with the inputs which the DDE require. This resulted in the possibility to directly assess two out of the nine LSC. This approach to combine two tools brings more clarity on under which circumstances it can be possible and an opportunity to directly integrate tailored sustainability criteria into DDE. It has previously been argued that the design community need to bring more attention to the integration of design tools ("method ecosystem") to better enable industrialisation of these (Gericke et al., 2020). One critical aspect of this is the consideration of the data- and information flow in design tools, where Mallalieu et al. (2022) showed that it is specifically a lack of this in developed Design for AM tools. This was clearly shown is this study as well where there is a mismatch with the data available (i.e., material data) and the time adding activities of manually analysing the LSC to enable direct assessment in the DDE. Continued research can investigate how this additional step in between LEASA and DDE can be formalised in a way that strengthen the reliability of the logical relationships. For this purpose, it would be interesting to explore for example group model building, in line with previous work within sustainable design such as (Watz et al., 2022). This can provide a procedure for ensuring that both relationships, and how these are quantified, are valid in the specific tool integration context. Furthermore, research within design exploration, such as the development of DDE, is currently being conducted, where Al Handawi et al. (2020); Liu et al. (2021); Martinsson Bonde et al. (2022) are examples of research within digital design exploration. This study provides input on where efforts can be put to enable direct integration of a systemic sustainability perspective in design explorations. At present, a qualitative approach e.g., Hallstedt et al. (2023), is still dominant for assessing several sustainability criteria in early phase design, which is visible in this study as well. Consequently, if only the partial spectrum of the LSC that can be directly integrated in the design space exploration, are used to inform e.g., trade-off analyses, there is a risk that decision-makers do not consider the systemic view of sustainability. Furthermore, if only a few of the LSC are used as proxy for the full sustainability performance of a solution, the risk for sustainability sub-optimisation remains, which contradicts the purpose of LSC. The sustainability criteria were in this study identified and formulated according to the four characteristics described in the Section 3.1. Another more integrated approach between LEASA and DDE can adopt a more opportunistic way of identifying sustainability criteria, where additional sustainability criteria could be selected and formulated based on 'the ability to be directly assessed in DDE'. Two examples of this would be: i*) Energy consumption during print*, where total print volume and material energy specific constants from experiments potentially could be used to approximate this. ii) The *durability of the TRS,* which can be approximated by adding an evaluation based on Paris' Law. In addition to the aim of the paper, the stepwise approach used to in this case study also indicated promising results in terms of breaking down complex high-level challenges into concrete capability needs. The approach supported in better understanding of what design support is needed for the challenge, and how individual design tools can become parts of method ecosystems. This can lead to more effective and efficient use of the design tools (Gericke et al., 2020; Mallalieu et al., 2022).

To conclude, the stepwise approach utilised in this paper supported in the breakdown of a complex challenge to identify two engineering design support tools in LEASA and DDE. These were combined and supports in assessing a systemic view of sustainability in early phase design explorations of additive manufactured components. Furthermore, it is recommended that more research is conducted on the link between LEASA and DDE to investigate the potential of more direct integration. It is also recommended that the stepwise approach utilised in this paper is tested further as it supported in the integration of the two design tools applied in this case study.

ACKNOWLEDGEMENTS

This paper was written in collaboration with GKN Aerospace, who participated in the case study.

The projects leading to this paper have been funded by the Swedish Innovation Agency (VINNOVA) through the DSIP project (ID 2020-04163) and the DIFAM project (ID 2019-02756).

REFERENCES

ACARE. (2022). *Fly the Green Deal* (tech. rep.). https://www.acare4europe.org

Al Handawi, K., Andersson, P., Panarotto, M., Isaksson, O., & Kokkolaras, M. (2020), “Scalable Set Based Design Optimization and Remanufacturing for Meeting Changing Requirements”, *Journal of Mechanical Design*, 143(2). http://doi.org/10.1115/1.4047908

Bertoni, A., Hallstedt, S. I., Dasari, S. K., & Andersson, P. (2020), “Integration of value and sustainability assessment in design space exploration by machine learning: An aerospace application”, *Design Science*, 6, e2. http://doi.org/10.1017/dsj.2019.29

Borgue, O., Valjak, F., Panarotto, M., & Isaksson, O. (2020), “Supporting additive manufacturing technology development through constraint modelling in early conceptual design: A satellite propulsion case study”, *Proceedings of the Design Society: DESIGN Conference*, 1, 817-826. http://doi.org/10.1017/dsd.2020.289

Carlsson, S., Mallalieu, A., Almefelt, L., & Malmqvist, J. (2021), “Design for longevity - a framework to support the designing of a product's optimal lifetime”, *Proceedings of the Design Society*, 1, 1003-1012. http://doi.org/10.1017/pds.2021.100

Dordlofva, C., Lindwall, A., & Torlind, P. (2016), “Opportunities and challenges for additive manufacturing in space applications”, *Proceedings of NordDesign, NordDesign* 2016, 1, 401–410.

Ford, S., & Despeisse, M. (2016), “Additive manufacturing and sustainability: An exploratory study of the advantages and challenges”, *Journal of Cleaner Production*, 137, 1573‑1587. http://doi.org/10.1016/j.jclepro.2016.04.150

Gericke, K., Eckert, C., & Stacey, M. (2017), “What do we need to say about a design method?” *Proceedings of the Design Society*, 7.

Gericke, K., Eckert, C., Campean, F., Clarkson, P. J., Flening, E., Isaksson, O., ... & Wilmsen, M. (2020), “Supporting designers: moving from method menagerie to method ecosystem”, *Design Science*, 6, e21. http://https://dx.doi.org/10.1017/dsj.2020.21

Hallstedt, S. I. (2017), “Sustainability criteria and sustainability compliance index for decision support in product development”, *Journal of Cleaner Production*, 140, 251–266. http://doi.org/10.1016/j.jclepro.2015.06.068

Hallstedt, S. I., & Isaksson, O. (2017), “Material criticality assessment in early phases of sustainable product development”, *Journal of Cleaner Production*, 161, 40–52. http://doi.org/10.1016/j.jclepro.2017.05.085

Hallstedt, S. I., Isaksson, O., Watz, M., Mallalieu, A., & Schulte, J. (2022), “Forming digital sustainable product development support”, *Proceedings of NordDesign, NordDesign* 2022.

Hallstedt, S. I., Villamil, C., Lövdahl, J., & Nylander, J. W. (2023), “Sustainability fingerprint - guiding companies in anticipating the sustainability direction in early design”, *Sustainable Production and Consumption*, 37, 424–442. http://doi.org/10.1016/j.spc.2023.03.015

Kravchenko, M., Pigosso, D. C., & McAloone, T. C. (2019), “Towards the ex-ante sustainability screening of circular economy initiatives in manufacturing companies: Consolidation of leading sustainability-related performance indicators”, Journal *of Cleaner Production*, 241, 118318. http://doi.org/10.1016/j.jclepro.2019.118318

Kwok, S. Y., Schulte, J., & Hallstedt, S. I. (2020), “Approach for sustainability criteria and product life-cycle data simulation in concept selection”, *Proceedings of the Design Society: DESIGN Conference*, 1, 1979–1988. http://doi.org/10.1017/dsd.2020.297

Liu, G., Xiong, Y., & Rosen, D. W. (2021), “Multidisciplinary design optimization in design for additive manufacturing”, *Journal of Computational Design and Engineering*, 9(1), 128–143. http://doi.org/10.1093/jcde/qwab073

Mallalieu, A., Hajali, T., Isaksson, O., & Panarotto, M. (2022), “The role of digital infrastructure for the industrialisation of design for additive manufacturing”, *Proceedings of the Design Society*, 2, 1401– 1410. http://doi.org/10.1017/pds.2022.142

Martinsson Bonde, J., Brahma, A., Panarotto, M., Isaksson, O., Wärmefjord, K., Söderberg, R., Kipouros, T., Clarkson, P. J., Kressin, J., & Andersson, P. (2022), “Assessment of weld manufacturability of alternative jet engine structural components through digital experiments”. *ISABE* 2022.

Nilsson, S., Sundin, E., & Lindahl, M. (2018), “Integrated product service offerings – Challenges in setting requirements”, *Journal of Cleaner Production*, 201, 879–887. http://doi.org/10.1016/j.jclepro.2018.08.090

Ramani, K., Ramanujan, D., Bernstein, W. Z., Zhao, F., Sutherland, J., Handwerker, C., Choi, J.-K., Kim, H., & Thurston, D. (2010), “Integrated sustainable life cycle design: A review”, *Journal of Mechanical Design*, 132. http://doi.org/10.1115/1.4002308

Schmidt, W. P. (2006), “Life Cycle Tools within Ford of Europe's Product Sustainability Index. Case Study Ford S-MAX & Ford Galaxy (8 pp)”, *The International Journal of Life Cycle Assessment* 11, 315–322. http://doi.org/10.1065/lca2006.08.267

Schulte, J., & Hallstedt, S. I. (2018), “Workshop method for early sustainable product development”, *Proceedings of International Design Conference, DESIGN*, 6, 2751–2762. http://doi.org/10.21278/IDC.2018.0209

Taguchi, G., & Clausing, D. (1990), “Robust quality”, *Harvard business review*, 68(1), 65–75.

Villamil, C., Nylander, J., Hallstedt, S. I., Schulte, J., & Watz, M. (2018), “Additive manufacturing from a strategic sustainability perspective”, *Proceedings of International Design Conference, DESIGN*, 3, 1381–1392. http://doi.org/10.21278/idc.2018.0353

Walden, D. D., Roedler, G. J., & Forsberg, K. (2015), “INCOSE Systems Engineering Handbook Version 4: Updating the Reference for Practitioners”, *INCOSE International Symposium*, 25(1), 678–686.

Watz, M., & Hallstedt, S. I. (2021), “Depth and detail or quick and easy? Benefits and drawbacks of two approaches to define sustainability criteria in product development”, *12th International Symposium on Environmentally Conscious Design and Inverse Manufacturing (EcoDesign2021)*, Virtual Tokyo, 1-3 December 2021, 640–647.

Watz, M., & Hallstedt, S. I. (2022), “Towards sustainable product development – Insights from testing and evaluating a profile model for management of sustainability integration into design requirements”, *Journal of Cleaner Production*, 346, 131000. http://doi.org/10.1016/j.jclepro.2022.131000

Watz, M., Johansson, C., Bertoni, A., & Hallstedt, S. I. (2022), “Investigating effects of group model building on sustainable design decision-making”, *Sustainable Production and Consumption*, 33, 846–862. http://doi.org/10.1016/j.spc.2022.08.005