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ADDITIVE MANUFACTURING FROM A STRATEGIC SUSTAINABILITY PERSPECTIVE

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Abstract
There are high expectations of additive manufacturing (AM) as a technology to improve manufacturing efficiency and reduce material waste. This study aims to clarify the sustainability advantages and challenges of AM technologies used in industry by testing and applying a strategic sustainability life cycle assessment in the early development stage. The result showed possibilities from using the tool and some areas of certain interest regarding improvement potentials of the AM technologies, i.e. value chain management, concept design, optimized material usage, and social sustainability.

Keywords: additive manufacturing, life cycle assessment (LCA), product development, sustainability, aerospace industry

1. Introduction
In the last few years the growth of Additive Manufacturing (AM) has been exponential in the aerospace industry. One of the reasons is that AM technologies possibly will be part of the solution to two large challenges that the manufacturing industry is facing, namely (1) reducing fuel consumption and (2) reducing material waste (OECD, 2017). These challenges are not only about the reduction of costs, but also about sustainability improvements. High expectations are set on these new technologies, but they also have sustainability challenges (Tang et al., 2016) Therefore, thorough assessments of the sustainability impacts of these technologies are needed (OECD, 2017).
In AM, products are built layer-by-layer to generate three-dimensional parts directly from CAD models (Ford and Despeisse, 2016) in comparison to traditional subtractive manufacturing, where unwanted material is removed from a block of material (Paris et al., 2016). AM was early used for prototyping, but later turned into an industrial process. There are many benefits with the technology, such as: freedom of design, customized design, high shape complexity (Ford and Despeisse, 2016), improved and stronger structures with fewer materials (Griffiths et al., 2016), a wide range of materials used for low volumes (Thompson et al., 2016), adaptable design in a short period of time (Paris et al., 2016), and reduced weight (OECD, 2017).
Various types of additive manufacturing technologies have been developed over the past decades, for example, Powder Bed (PB), i.e., powder is spread out and a welding source melts the desired powder before another layer is spread, and Metal Deposition (MD), i.e., powder or wire is fed into the welding source and melted into desired shape. Both PB and MD can use different welding technologies and the AM technology is named thereafter. Electric Beam Melting (EBM) is a PB technology using electric beam welding, and Selective Laser Melting (SLM) is a PB technology using laser welding. When MD technology is used with laser it is simply called Laser Metal Deposition (LMD), an extra "W" indicates that wire is used. When powder is used the technology is often called 'blown powder'.

Depending on the requirements on the product, one AM technology might be more suitable than another to manufacture a specific product due to, e.g., material, shape, function, etc. Sometimes certain AM technologies might not even be possible to use, because of technical limitations or material requirements. However, from a sustainability perspective more knowledge is needed to assess the advantages and disadvantages with each technology in order to make a more sustainable manufacturing choice in early product development.

1.1. Strategic sustainability assessment method

For the sustainability assessment of AM, this research is utilizing the socio-ecological sustainability principles (SPs) from a backcasting perspective (Quist et al., 2011), included in the Framework for Strategic Sustainable Development (FSSD). The SPs state that in a sustainable society, nature is not subject to systematically increasing (1) …concentrations of substances from the Earth's crust, (2) …concentrations of substances produced by society, (3) …degradations by physical means, and, in that society people are not subject to structural obstacles to (4) health, (5) influence, (6) competence, (7) impartiality, and, (8) meaning-making. (Broman and Robèrt, 2017).

Sustainability Life Cycle Assessment (SLCA) is a qualitative method to identify challenges and strengths in the complete life cycle of a product, evaluating both the environmental and the social dimensions (Hallstedt et al., 2013), also recognized as Strategic Life Cycle Management in Ny et al. (2006). The SLCA has a life cycle thinking perspective, evaluating all cycle stages. It uses the SPs to identify hot-spots of sustainability impact in a fast and easy way and can provide immediate information, which is relevant in the early stages of the product development processes (Hallstedt et al., 2013).

1.2. Aim and purpose

Previous applications of the SLCA have shown that it allows designers and decision makers to identify potential sustainability issues, business opportunities or knowledge gaps that may require further investigations (Ny et al., 2006; Borén and Ny, 2016). *The purpose with this study is therefore to test and verify the applicability of an adapted version of SLCA, called SLCA2.0, as a tool to strategically assess a technology in the early development phase from a sustainability perspective*. From an industrial perspective, AM technologies and manufacturing machines need to be improved from a sustainability viewpoint. The following research question is used to guide this study: *What sustainability challenges, opportunities and improvements can be identified for some selected AM technologies from a strategic sustainability perspective?*

2. Method

A three-stage research approach was selected and is illustrated in Figure 1. The three stages: systematic literature review; an industry case; and, a SLCA2.0 workshop have different detailed steps that will be explained in the following sub-sections.

2.1. Systematic literature review on sustainability assessment of AM

A systematic literature review on sustainability assessments of AM was conducted, which had the purpose to: 1) determine the state of the art of AM technologies in relation to sustainability opportunities, challenges and assessments; 2) identify tools, methods or frameworks that can be useful for considering sustainability aspects in AM processes; and, 3) detect gaps and opportunities in the field. The literature review was structured with guidance from the descriptive study by Blessing and Chakrabarti (2009) to establish a systematic process. Firstly, keywords for the study were determined, e.g., "Metal Additive Manufacturing", "Sustainability assessment". Secondly, the SCOPUS database was selected, and thirdly the research was limited from 2007 to 2017, with the following query: TITLE_ABS-KEY ((Additiv* AND manufactur*) OR (3D* AND Print*) AND (Sustainab* OR Assessment* OR eco* OR (life cycle) OR efficien*) OR (aerospace* AND metal)) AND PUBYEAR > 2007). A snowballing process (Wohlin, 2014) was performed. The papers were evaluated by relevance by reading the title, abstract, conclusions and keywords, giving a final list of 54 papers. The papers were listed in a worksheet, following guidance by Karlsson et al. (2009), to ease the structuring and analysis of the articles. The papers were organized by year, title, author, keywords, AM technology and used tool, i.e., for considering sustainability aspects. Following the guidance of Blessing and Chakrabarti (2009), a brief summary of each paper was done. Finally, the papers were analysed, identifying assessment variables, tools, gaps and challenges. The results were essential to constitute the conceptual foundation for the next steps in the research: the industry case and the SLCA2.0 workshop.

2.2. Industry case

GKN Aerospace Engine Systems (GKN) is a supplier to all major aerospace original equipment manufacturers of aircraft engines. The company perceives a market potential with AM for their metallic structural aero engine components due to its potential for cost savings, decrease of weight, added functionality, and repair services. The materials currently used for AM are mainly titanium and nickel alloys, i.e., Titanium 6-4 and Inconel718. However, also Titanium 6242 and Haynes 282 are considered to be used for AM in the future. The literature review was a straightforward way to identify key aspects in the industry case and to structure the research approach that followed (see Figure 1).

2.2.1. Interviews and observations

The industry case study started with a review of company documents such as, the design practice for AM. After that, ten individuals working with AM in different positions, within areas such as design, material, and production, were selected for an interview study and relevant questions were prepared. The interviews were semi-structured with open-ended questions, approximately one hour long. In addition to the interviews, observations were made during internal company meetings about AM and related topics. The findings were gathered and analysed according to the SPs.

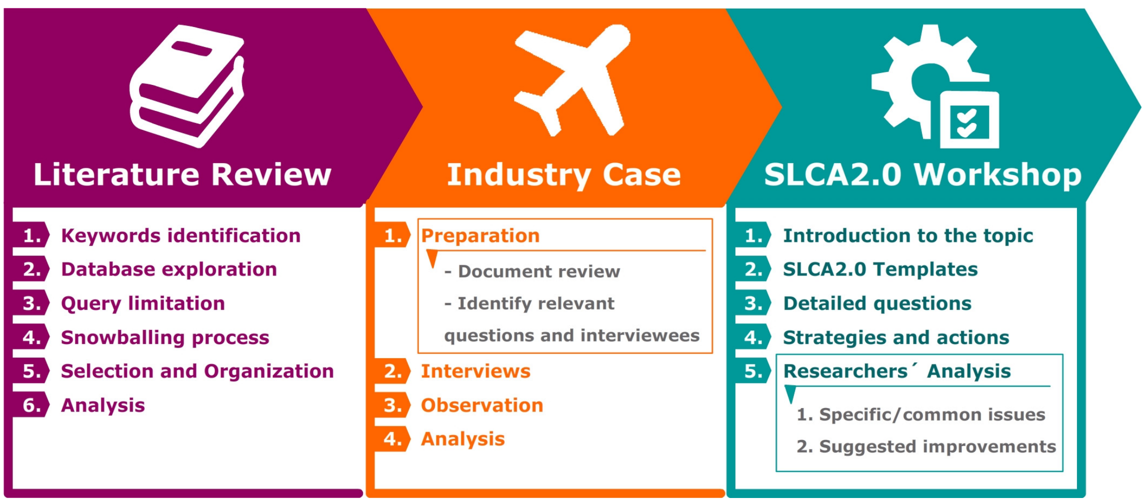

Figure 1. Three-stage research approach used in this study

2.3. SLCA2.0 workshop

Supported with the results of the literature review and the interviews, an adapted version of an SLCA, called SLCA2.0, was conducted to identify the most important sustainability opportunities and challenges of some selected AM technologies in the early development phase. The selected AM technologies were: i) Powder bed: EBM and SLM; ii) Powder deposition (or blown powder) for two materials: a titanium alloy and a nickel alloy; and, iii) wire metal deposition (LMD). A workshop was performed with ten AM practitioners from the case company in the areas of design, production and management. The workshop process was divided into different steps, see Figure 1. First, an introduction to the area of Sustainable Product Development (SPD) was given, explaining the integration and implementation of a strategic sustainability perspective into the early phases of the product innovation process, including life-cycle thinking. In addition, a description of the workshop templates was provided, covering the three dimensions of sustainability (ecological, social and economic) and generic phases of a product's life cycle. Some guided questions for each dimension were included, see Table 1. These questions were derived from using the SPs and the tactical sustainability design guidelines defined in a previous study describing the sustainability design space (Hallstedt, 2017). In contrast to the SLCA presented in Ny et al. (2006) and Hallstedt et al. (2013), the economic dimension was added in this assessment, to cover the company perspective and their organisational influence and impact on the sustainability performance. In addition, guided questions and templates were developed and used as a progression of the original SLCA version. The workshop participants were then divided into three groups to fill in the SLCA2.0 templates. A brief assessment of the selected AM technologies was carried out in a brainstorming exercise for each life-cycle phase, in relation to the ecological, social and economic dimensions of sustainability. In the next step, specific questions regarding each of the SPs were used to collect detailed information for each AM technology, as a complement to the overarching templates used in the previous step. An excerpt of a set of specific SPs-questions, also derived from guidance of the SPs and tactical design guidelines, is shown in Table 2. A total of 51 questions were used to cover an overall of the SPs. The assessment step was followed by a group discussion from which examples of strategic actions for overcoming the identified issues were listed. Finally, researchers merged the result and analysed the workshop outcome in two steps: 1) highlighting specific issues for each of the studied AM technologies and summarizing common issues; 2) suggesting improvements also including AM practitioner's alternatives.

Table 1. SLCA2.0 template with some examples of guided questions

		Ecological dimension	Social dimension	Economic dimension
Life cycle phases	Guided questions	Guided questions		
Raw material extraction Manufacturing Post – process Usage maintenance Upgrading, end of life	What sustainability challenges and/or strengths does the current process have?	Are there any materials or activities used that are dependent on: metal alloys, chemicals, usage of fertil land and/or clean water usage?	Are there any conflict minerals/metals and/or hazardous chemicals used in any of the life cycle phases?	Are there enough developed collaborations in the value chain?

Table 2. Excerpt of the detailed questions template with some example questions

Detailed questions - sustainability principles (SPs) 1-8	Yes, no, don't know	Response notes and references to data source	
		AM technology alternative 1	Difference to AM technology alternative 2
SP1 - Are there any risk metals/alloys used, that have a high environmental impact or that are rare or have limited availability?			
SP2 - Are you currently using chemicals that are non-degradable, bio-accumulating or are listed in the SIN or the REACH candidate lists? If yes, can they be avoided?			
SP3 - Does raw material extraction or production cause damage to nature by physical means (e.g. deforestation or open pit mining)? If yes, specify how.			
SP4 – 8 Are concerns of community in the surrounding of suppliers of raw materials actively solicited, impartially judged and transparently addressed?			

3. Results

In this section, the results of the literature review, industry case and SLCA2.0 workshop are presented.

3.1. Literature review results

From a sustainability perspective, there are advantages and challenges with AM technologies (OECD, 2017), and some of them are listed in this section as: design, recycled materials, reuse of powder, waste, assessment tools, energy consumption and social perspectives.

Design: AM allows the adding of value by customizing components, without increasing the manufacturing costs (Baumers et al., 2016). A CAD model can be modified according to the product requirements, improving its properties in the early stage of the process (OECD, 2017). With parameters of natural cellular structures (as bones), it is possible to increase the resistance and to reduce material use, weight, and emissions (Williams et al., 2011). With an optimized design, the weight of a part can be reduced in a range of 35 to 65% (Ahn, 2016). When the aircraft weight is reduced, the fuel consumption and related emissions are reduced as well (OECD, 2017). Some AM printers mix different materials in one process, which reduces the number of parts in comparison to traditional manufacturing, but makes the disassembly process challenging (OECD, 2017).

Recycled materials: In many cases, the raw materials used in AM processes are not from recycled sources (OECD, 2017). Aerospace components demand very high-quality performance, resistance, durability, etc. Those attributes can be ensured by using virgin materials (Eckelman et al., 2014). For that reason, it is not possible to use only recycled materials in the process.

Reuse of powder: It is possible to reduce cost, waste and emissions, if the amount of virgin AM raw material is reduced (Dawes et al., 2015). In some cases, reused powder was found not to change its properties considerably (Petrovic and Niñerola, 2015). Other studies found the particle size of reused powder to be problematic (Fulga et al., 2017), requiring powder treatment (Le Bourhis et al., 2014). In EBM and SLM, it is important to test the process and the powder (Nandwana et al., 2016; Mellin et al., 2017).

Waste: Traditional manufacturing, e.g., milling, removes about 87% of the material, turning it into waste, which needs to be recycled (Paris et al., 2016). For LMD-wire the waste is zero or minimum, for EBM: “almost 70% of the powder leaving the nozzle becomes waste” (Ma et al., 2017), the un-used material has to be treated for later usage in other products (Verma and Rai, 2017). Depending on the surface requirements, there is a waste material as the result of subtractive post-processes (OECD, 2017).

Assessment tools: The most used tool to assess AM is Life Cycle Assessment (LCA), i.e. the analysis of the environmental impacts in all the stages of a product life cycle: from raw material extraction to the end of life. Traditional manufacturing is used as a comparison point and is found to have more environmental impact than AM (EBM) (Paris et al., 2016). Due to the variety of materials, methods, technologies and variables in AM, it is necessary to adapt the LCA (Tang et al., 2016). LCA results are related to weight reduction, energy consumption, waste, number of pieces, the size, the shape, the material, the maximum utilization of the machines, etc. (OECD, 2017). For SLM, the use of gases in the process has a significant impact (Kellens et al., 2011). Due to LCA complexity, amount of data, and resource limitation, most of the assessments focused only on the AM manufacturing phase, excluding the environmental impacts generated in the other product life-cycle phases (Nimbalkar et al., 2014). Unknown materials and processes can cause uncertain long-term effects (Chen et al., 2015). Some AM raw materials can have a high rate of environmental impacts, can be difficult to extract, are scarce or have social implications, known as “critical materials” (Graedel et al., 2015). The "conflict materials" are critical materials that are extracted or manufactured in conflict areas, where war and human rights violations mark these materials as conflict materials (European Commission, 2017). Some of the alloys used in AM contain a small amount of conflict materials. With a method to assess criticality it is possible to assess metal alloys from an availability and sustainability perspective in the early phases of the product development process (Hallstedt and Isaksson, 2017).

Energy consumption: The most common research area, comparing AM with traditional manufacturing, or with different AM scenarios, is energy consumption (Tang et al., 2016). Nimbalkar et al. (2014) showed that AM could reduce the total energy consumption for an aerospace component by 65%. The purity of AM raw materials for aerospace components requires high temperatures in the process, which demands a high energy consumption (Eckelman et al., 2014). It is possible to decrease the energy consumption if the AM machine is used at full time and capacity (Faludi et al., 2015), if the machine idle/off state can be optimized (Faludi et al., 2016), and if the geometry and the position in the machine are correct (Verma and Rai, 2017). Other energy consumption factors consist of removing the part from the platform (Kellens et al., 2017) and improving the component surface with subtracting processes (Jackson et al., 2016); some EBM components can be separated by hand (Baumers et al., 2016).

The social perspectives: While there is some research on the environmental implications of AM, the social dimension is largely absenting in previous analyses. There is insufficient stakeholder analysis and a lack of a holistic view of the complete picture of the product life cycle (Mesquita et al., 2016; Missimer et al., 2017). However, previous studies have pointed at workers' health that can be affected by the contact with toxic materials, particles, high temperature, etc. (Faludi et al., 2015), in addition to a risk that the large-scale implementation of AM could cause massive job loss (OECD, 2017).

3.2. Industry case study results

For the industrial case, some areas were identified: design, repair and redesign, recycled material and waste, energy consumption and emissions, health and safety; these areas are described below.

Design, repair and redesign: From the investigation at the case company it was concluded that AM enables a more complex design. For example, it is possible to make parts that are topology optimized or hollow, i.e., honeycomb or cooling channels, which adds functions and decreases weight. Light weight has a strong correlation to fuel consumption and thereby to emissions in the aerospace industry. The materials used for AM at the case company are mainly titanium alloys and nickel-based alloys. Some of those alloys could contain critical materials, since they include elements that are critical from a sustainability and availability perspective according to the method for assessing alloys (Hallstedt and Isaksson, 2017). However, the aerospace industry has high quality requirements so the materials need to be aerospace certified. This fact delimits the degrees of freedom for selecting materials. Metal deposition is also used to repair and re-design products. One example is a 190 kg product that was found to be too weak (thin) in certain areas. Blown powder was used to add 2.5 kg material on this particular area, which hindered the product from being discarded.

Recycled material and waste: Information about the rate of recycled material being used in the powder manufacturing was difficult to access. The supplier was not willing to share this information, as it is closely linked to finance. Currently there are no requirements stating that certain amounts of recycled material should be used in the AM powder processes, but there is no obstacle to setting such a requirement. The powder in both SLM and EBM is reused. However, the powder in EBM is pre-sintered, which limits the possibility for reuse to a high degree, as it first needs to be blasted. In blown powder, the pump that regulates the powder feed process through the nozzle is not synchronized with the welding machine. As a result, when short stops are made in the AM welding, the powder pump is not turned off and the powder is then collected in a container as waste. Therefore, the powder waste is larger in blown powder compared to powder bed technologies. However, the powder could potentially be reused. The amount of support structure needed in powder bed technologies varies depending on the product design. In SLM, the support structure needs to be more stable, compared to EBM, due to the pre-sintering in EBM. The support structure cannot be reused as it is waste that is recycled. In blown powder, there is no support structure. The virgin plate that is at the bottom of the powder bed is reused. After use, the surface is grinded and reused. When it has become too thin for reuse, it is recycled.

Energy consumption and emissions: A substantial amount of energy is needed in the manufacturing of powder and argon, as well as an AM process and after-treatments. The energy consumption varies between different machines. There is ongoing work at the company to reduce energy consumption. Large amounts of argon or nitrogen are used in the AM process in the nozzle as rotary gas, protective gas, and for carrying the powder. However, the air contains both argon and nitrogen naturally. Therefore, it is not considered to be an environmental problem; it is rather an economic one. The company is considering the possibility of re-using argon gas. Emissions from after-treatments depend clearly on the after- treatments that are used, which in turn depends on the quality requirements. Generally, AM requires less processing compared to castings and forgings, although some processing is needed, especially for aero functional surfaces. For powder beds, Hot Isostatic Pressing (HIP) is used as after-treatment. However, HIP is never used after blown powder AM, if the build is on top of a forging, since forgings cannot be HIPed. In this case, the product is heat-treated with. e.g. stress relieve instead. These processes have no emissions of concern, but are energy intensive.

Health and safety: Titanium is one of the most combustible metal dusts. Titanium explosion is a risk for all welding with titanium, not only AM. The use of argon prevents explosion, but the risk occurs in the ventilation, where the dust is exposed to oxygen and the air stream can become an ignition source. This risk is higher with powder beds, due to the various sizes of particles, which require different effects for melting. The risk is smaller with blown powder since the powder is larger than dust. The question is at what point oxygen can be introduced without a risk of explosions. Using inert gases such as argon also entails health risks. The gas is heavier than air, which leads to the risk of fainting from lack of oxygen. There is also the risk of welders breathing toxic fumes and weld particulate. Dust accumulation on floors and steps creates a slip and fall hazard as well. Appropriate safety processes are therefore important, as well as appropriate protection suits, including face masks and gloves. Health and safety during the use of an AM product is not different from other manufactured products. However, with new technologies and processes comes the need for aero-certifications for airworthiness and flight safety. Certification of airworthiness is initially conferred by an aviation authority, the European Aviation Safety Agency (EASA).

3.3. SLCA2.0 workshop results

Tables 3 to 5 present the summarized results of the workshop. They show that all groups listed misalignments (or alignments) to the ecological SPs, and some related to specific AM technologies. Possible positive contributions are highlighted with green. The social SP's were difficult to assess on a detailed level for all participants. For the economic dimension, disadvantages are generally mentioned in terms of costs, while advantages are framed as business opportunities and competitiveness. The strategies and actions for overcoming the sustainability challenges are shown in Table 6.

The results from the SLCA2.0 workshop showed that sustainability impacts could be listed in all sustainability dimensions and for all three AM technologies. Energy intensity, value chain uncertainty, use of critical metals and hazardous chemicals can be identified as common sustainability hotspots for the AM technologies for the case company. The identified advantages involve a potential for new business opportunities. The 32 detailed questions related to the social dimension were to a large extent answered with "I don't know", which highlights the lack of apprehension regarding social aspects of product development among AM practitioners. The participants were aware of the opportunities, gaps and the relevance of the environmental and social dimension related to this technology.

Table 3. Summary of the ecological sustainability assessment of three AM technologies

<table>
<tr><th>Life cycle phase</th><th>Powder Bed (SLM and EBM)</th><th>Blown Powder</th><th>LMD (Wire)</th></tr>
<tr><td rowspan="2">Raw Material Acquisition</td><td colspan="2">Re-use of powder material possible to some degree (SP1)
Energy intensive process for powder production (SP1)</td><td></td></tr>
<tr><td colspan="3">Systematic increase of concentrations of heavy metals (SP1) and persistent chemicals (SP2), as well as land and water use and contamination of eco-systems (SP3) due to mining activities
Systematic increase of concentrations of fossil carbon-dioxide (SP1) and NOx (SP2) depending on energy use for e.g. extraction, transportation, and manufacturing of the raw material</td></tr>
<tr><td rowspan="2">Manufacturing</td><td>SLM requires less energy than EBM (SP1+2)
Support structures difficult to reuse, need to be recycled
Recycling of Argon could reduce energy consumption</td><td>Challenge with filtering of metal powder in outlet (SP1)</td><td>No waste from the wire, all wire is used</td></tr>
<tr><td colspan="3">Systematic increase of concentrations of fossil carbon-dioxide (SP1), NOx and persistent chemicals (SP2) depending on energy use</td></tr>
<tr><td rowspan="2">Post-processing</td><td>SLM requires less energy use for surface treatment compared to EBM</td><td></td><td>Double heat treatment</td></tr>
<tr><td colspan="3">Systematic increase of concentrations of fossil carbon-dioxide depending on energy use
Post-processing (e.g. chemical milling) likely uses chemicals that could systematically increase in concentration (SP2) and cause eco-system degradation and water use (SP3)
Due to low tolerances in AM, there is less need for after-treatment</td></tr>
<tr><td>Use and maintenance</td><td colspan="3">Easy maintenance, re-design and repair leads to longer life-span and lower need for raw-materials, manufacturing, etc. in comparison to traditional processes
Optimized design and more design freedom leads to lower weight and higher fuel efficiency</td></tr>
<tr><td>End-of-Life</td><td colspan="3">Recycling of the material possible (not necessarily for the same process again)
Heterogeneous component materials may make recycling more difficult</td></tr>
</table>

Table 4. Summary of the social sustainability assessment of three AM technologies

Life cycle phase	Powder Bed (SLM and EBM)	Blown Powder	LMD (Wire)
Raw Material Acquisition	Conflict materials (SP4-8) Effects on local communities, potential displacement, land grabbing (SP4-8) Working conditions and rights in the supply-chain (SP4-8)		
Manufacturing	Inhalation of inert gas and particles can be a health risk, e.g. suffocation, respiratory diseases (SP4) Explosion risk with Ti powder (SP4)		
	Limited risk for accidents with laser (SP4) Possibilities for competence building with AM, e.g. new technology, application, design freedom, etc. (SP6) Risk for reduction of jobs (4-8)		
Post-processing	Post-processing like chemical milling or blasting can pose health risks due to e.g. particles and chemicals (SP4)		
Use and maintenance	Uncertain effect of AM on flight safety, e.g. occurrence of defects (SP4)		
End-of-Life	Value chain, employees uncertain working conditions and rights (4-8) Job opportunities with urban mining (SP4-8)		

Table 5. Summary of the economic sustainability assessment of three AM technologies

Life cycle phase	Powder Bed (SLM and EBM)	Blown Powder	LMD (Wire)
Raw Material Acquisition	SLM demands a specific powder size that is more expensive than the one used for EBM		
	Powder is more expensive than ingots		
	It is cheaper to by simple forged parts and to add complexity with AM than to buy complex forged parts. High material efficiency – low Buy-to-Fly Ratio Less developed supplier network and fewer suppliers worldwide Investments in material testing and databases needed		
Manufacturing	Upholding the required vacuum is energy intensive and costly Costs related to argon use Difficult to reuse the support structure/bottom plate SLM has less freedom in geometry than EBM		
	AM enables cheap and fast prototyping, reduction of lead-time Potentially limited machine capacity Lower technology maturity (TRL), which implies higher risks and more need for controls New competencies for AM technology needed		
Post-processing	SLM requires less post-processing than EBM		
	Less after-treatment because AM has smaller tolerances Post-processes demand chemicals that could be or become restricted and need to be replaced, which causes costs Lower machining cost and related cost of waste-streams		
Use and maintenance	New business opportunities: new business models, optimized design, remanufacturing, repair, etc., higher value and lower costs Just in time production of spare parts Easier to redesign		
End-of-Life	Incentives to create more closed loop solutions with AM		

Table 6. Summary of the strategies and actions for AM technologies

Strategies and actions for AM technologies: Powder bed and Metal deposition
Optimize product design regarding sustainability performance in the use phase (e.g. surface, structure) and minimize need for support structure in powder bed processes. Control process risks (e.g. explosion of titanium powder) Explore opportunities in AM repair methods in the aerospace field and other fields Support and encourage current and possibly new stakeholders to prolong the lifecycles of AM products and -materials. This could be done by e.g. creating loops in the manufacturing stage (100 % reuse of powder) or by recycling or reusing material in the late life cycle stages of the AM components. Understanding and collaboration inside the company and the supply chain. Increase AM specialized competence Use of renewable sources of energy and re-use the inert gas (Argon) Wide application of AM and development of quality parts that require less testing Deal and collaborate with suppliers to get sustainable raw materials and avoid material criticality (e.g. conflict materials)

4. Concluding discussion

There are clear sustainability challenges with additive manufacturing, even though the technology has a great potential to be part of a more sustainable production. Several issues were identified for some selected AM technologies using a simplified support tool called SLCA2.0. These issues encompassed challenges, opportunities and improvement suggestions and they have been grouped according to different areas, i.e., value chain management, concept design, optimized material usage, and social sustainability. In this study, the tool SLCA2.0 was tested and its applicability and usefulness for making a strategic sustainability assessment of technologies in the early development phases was verified.

Value chain management

In the manufacturing industry, including AM, there is a risk to use critical materials, which have negative social and environmental impacts. To avoid this problem, it is necessary to have a continuous collaboration with suppliers and customers in the value chain. For the case company, this means that the purchasing and marketing departments need to contribute with expertise and competences. The option to change materials in the specific case of aerospace industry is complicated in practice as there are high quality requirements of the components for this specific sector and there are few suppliers that comply with all the aerospace regulations.

Concept design, repair and redesign

AM is a useful technology to develop and improve the components and the component design can be adapted with minimum cost, compared with traditional manufacturing. An appropriate design can reduce the amount of parts, have more functionalities, and use less materials (OECD, 2017). If the technology is used to maximize its design potential for topology optimization and light weight design, material efficiency is maximized (Griffiths et al., 2016). This results in lower fuel consumption and thereby less emissions during use, which is a central sustainability challenge in the industry. Another positive sustainability potential with AM technology is the possibility to use it to repair or re-design, and thereby extend the life-time of the product. This could result in new business opportunities for manufacturers as product service system providers.

Optimized material usage

AM technologies have sustainability impacts that are similar to other types of production processes. However, the buy-to-fly ratio, i.e., the initial material mass and the material mass that remains in the manufactured component, for titanium aerospace components is between 12:1 to 25:1 for traditional manufacturing (Oak Ridge National Laboratory, 2010), and for AM it is approximately 1.5:1 (Huang et al., 2016). This means that the AM technologies have a low percentage of wasted materials. Handling waste and reuse of powder is one of the greatest challenges. However, if the reuse of powder is maximised, the support structure is optimized, and the surface machining is minimized, the amount of scrap and material waste can decrease.

The literature review identified several studies showing different results regarding the effect of powder reuse on the powder properties. This highlights the need for more investigations on this matter. The aerospace industry cannot risk using unqualified powder in their products, since it potentially can lead to low-quality products and cracks that can have lethal consequences. The same is valid for using recycled material in the manufacturing of powder. The case company is therefore researching and testing to reuse the wasted powder in addition to reduce the waste and the post-treatments.

Social sustainability

Regarding social sustainability, there is minimum research in the literature about sustainability assessment of AM and the social impacts that the AM technologies might cause in the complete life cycle of the components. Academic researchers are mainly focused on the workers of the manufacturing phase, leaving behind stakeholders that can be affected in other life-cycle stages; in the raw material extraction, e.g., a community might be affected by mining processes. In the industry case, there is knowledge about the social sustainability impacts, however more academic research on the complete sustainability life cycle impacts of AM is needed.

SLCA2.0 potentials and limitations

The study showed that the SLCA2.0 was a useful tool that can be used to identify a list of challenges and opportunities, as well as possible strategies to improve the process from a sustainable perspective in the early stage of the product development process. The SLCA2.0 is different to a traditional LCA, as a LCA requires a lot of time, software resources and data. Specifically data is a challenge to obtain in the initial stages of the process, which makes it less useful. Some positive characteristics with the SLCA2.0 include the following: it does not demand expertise and detailed data, a multi-functional team can contribute with their competences and experiences, it is possible to get valuable data for future industry improvements, it is a quick guide for the early stages of the product development process, it assesses the ecological, social and economic dimensions of sustainability using socio-ecological sustainability principles that is claimed to be scientific, necessary, sufficient, concrete and non-overlapping (Ny et al., 2006), and it includes the complete product life cycle applying a backasting perspective. Covering all stages of the product life cycle is considered important for a reliable AM assessment, according to Meteyer et al. (2014). Practitioners reflections from the sustainability assessment raised awareness that will encourage them to work with their external stakeholders. However, some limitations of the SLCA2.0 were also concluded: the assessment is dependent on the facilitator's skills and knowledge in the area of sustainability, the results rely on the team's expertise with the risk of neglecting some important aspects due to their lack of experience and knowledge of the technologies assessed, and the outcome is qualitative and does not provide a visualisation of the result.

Future work

The workshop results indicated an awareness of the sustainability challenge and interest for improving the aerospace industrial processes from an ecological, social and economic perspective. There are several areas that can be researched to improve the sustainability performance of AM technologies, such as how to accomplish a deeper assessment of AM technologies by using different tools or approaches that help to include a holistic perspective, encourage the stakeholders in the supply chain to research and improve the process, generate collaboration with other industry sectors, get a better understanding of social sustainability aspects related to the technologies, investigate thoroughly the quality of components manufactured with reused powder and recycled materials, and more efficient and low-risk infrastructure regarding AM machines and processes in terms of energy consumption, waste, production time, quality, health, etc.

It is necessary to verify the effectiveness of the tool SLCA2.0 by applications in other industry sectors, adapting and improving the structure and possibly complementing it with other tools or methods, with the purpose of securing accurate outcomes of the assessment.

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