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Innovation in a box: exploring creativity in design for additive manufacturing in a regulated industry

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ABSTRACT

Additive Manufacturing (AM) is often considered to increase opportunities for creativity in design compared to traditional manufacturing methods. At the same time, it is suggested that regulated work can have a negative effect on engineers' creative abilities, which are linked to three components of creativity (expertise, motivation, and creative thinking skills). Due to the 'newness' of AM, engineers need to broaden their expertise to fully exploit their creative potential while using AM. Previous research has presented support tools to assist engineers to understand the complexity of AM. A majority of such studies focus on novice engineers, rather than providing an understanding of how AM is involved in industrial practices. This paper follows three case studies from the space industry, a regulated industry, that aims to re-design a product for AM over a 21-month time period. The purpose is to explore how restrictions affect engineers' opportunities to build AM expertise for creativity in a regulated industry. Results show the importance that case-specific aspects have on an engineer's learning path for adopting AM. Engineers find themselves in a complex situation, with a conflict between being 'safe' or innovative, where innovation within such regulated industries is often compared to innovating 'in a box'.

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DfAM; design for space; AM knowledge; design restrictions

Introduction

Involving Additive Manufacturing (AM) in design practices is often considered to increase the opportunities to create product innovations through a higher degree of design freedom (Leutnecker-Twelsiek, Klahn, and Medboldt 2016; Klahn, Leutenecker, and Meboldt 2015). Hence, there are opportunities to bring various AM design potential into the design. 'AM design potential' in this paper refer to the multiple possibilities to increase a product's value through *geometrical*, *hierarchical*, *material,* and *functional* complexities (Gibson, Rosen, and Stucker 2015). In an attempt to support engineers to fully utilise AM design potentials, previous research has presented various Design for Additive Manufacturing (DfAM) methods for design practices (e.g. Kumke et al. 2018; Rias et al. 2017; Rosen 2016; Klahn, Leutenecker, and Meboldt 2015; Laverne et al. 2015; Maidin, Campbell, and Pei 2012; Agrawal 2022). However,

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a study on DfAM teaching showed that current higher education does not provide a path for novice engineers to revolutionise the way they design products with the risk that future engineers will design product similar to the ones made for traditional manufacturing technologies (Borgianni et al. 2022). To increase the possibilities to take full advantage of DfAM, Prabhu et al. (2020) highlighted the need to include both opportunistic and restrictive DfAM to reach creativity and fully utilise AM in design. In relation to this, Prabhu et al. (2022b) found that the experienced self-efficiency of using AM in design was related to both opportunistic and restrictive DfAM. Others have emphasised on specific tools and methods to support ideation to manage these design complexities and ultimately the new design freedom, such as Design Heuristics (Blösch-Paidosh and Shea 2022; Blösch-Paidosh and Shea 2021; Blösch-Paidosh and Shea 2019; Blösch-Paidosh and Shea 2017; Lindwall and Törlind 2018), Design Principles (Perez et al. 2019; Lauff et al. 2019; Valjak and Bojčetić 2019), and Design Guidelines (Allison, Sharpe, and Seepersad 2019; Thompson et al. 2016; Klahn, Singer, and Meboldt 2016; Kranz, Herzog, and Emmelmann 2015), all specifically designed for AM. A majority of the studies have focused on evaluating how novice engineers comprehend the new design space given by AM through the various tools and methods. There is, however, still a lack of understanding of the involvement of AM in industrial practice (Pradel et al. 2018), especially in regard to exploiting engineers' creative abilities.

Since it has been suggested that highly regulated work can disrupt engineers' creative abilities (Amabile 1998), there can be a problem in fully utilising AM design potential while designing for AM in regulated industries, such as the aerospace industry. In the space industry, there is an ongoing shift towards more dynamic and, in some sense, less regulated development activities, with so-called 'new space', where many new and innovative companies have appeared on the market. Examples of such companies are SpaceX, Blue Origin and Virgin Galactic. However, since the industry to a large extent is still dependent on governmental funding, it can be argued that it is still restricted. Development projects in regulated industries often include clear gates which aims to gain trust in as well as prove a design (Lindwall, Dordlofva, and Öhrwall Rönnbäck 2017; Cooper and Sommer 2016). Such gates aim to address various restrictions, such as fulfilling airworthiness requirements. It is unclear how engineers can navigate restrictions to utilise AM potentials in design, ultimately allowing them to unleash their creative abilities. Restrictions is in this paper defined as the collection of industry regulations, limitations (design constraints and AM limitations), and conservatism. An engineer's creative ability is linked to the three components of creativity: *expertise*, *motivation,* and *creative thinking skills,* as described by Amabile (1998). AM is still a relatively new manufacturing method and consequently AM *expertise* can be argued to be the component that designers need to develop in order to fully use their creative abilities with AM. Additionally, an engineers' ability to adopt AM in design is dependent on their previous knowledge and experience on engineering design (Prabhu et al. 2022a). Therefore, the relation between creating expertise and utilising AM design potentials needs to be further studied (Pradel et al. 2018; Lindwall and Wikberg Nilsson 2021).

All this implies that engineers have two kinds of restrictions to take into account while adopting AM, i.e. industry regulations and AM limitations. The purpose of this paper is to explore how restrictions affect engineers' opportunities to build AM expertise for creativity in a regulated industry. The case studies presented in this paper are from the highly-regulated space industry, which show opportunities for involving AM in design (Gibson 2017).

Theoretical framework

To further understand how restrictions affect engineers' opportunities to build AM expertise for creativity, the first step is to establish an overview of previous research. This section contains a literature review with an overview of 'design potential of additive manufacturing', 'creating knowledge in design', and 'restrictions and creativity'.

Design potentials of additive manufacturing

Since it has been suggested that engineers can struggle to comprehend the new design freedom that AM can provide (Campbell, Bourell, and Gibson 2012), previous research has presented tools and methods to assist engineers to understand various AM design potentials in their design practices. Design practices in this paper refer to the practice of conducting design activities. Rosen (2014) have highlighted four unique AM complexities (*geometrical*, *hierarchical*, *material,* and *functional*) to categorise AM design potentials, all with the opportunities to rethink design and take advantage of the 'new' capabilities of AM processes. AM design potentials are supported through *design guidelines*, *design heuristics* and *design principles* that present the possibilities and limitations of AM processes related to design. Design guidelines are described as directions for engineers where process-dependent variables specifically direct the design to be optimised towards a specific AM process, through perspectives such as part orientation, support material removal and surface roughness on build angle (Allison, Sharpe, and Seepersad 2019; Mani, Jee, and Witherell 2017). These guidelines need to be considered to ensure that the design is manufacturable. Design heuristics often focus on early ideation and inspiration, guiding engineers to design a product to utilise the various design capabilities offered by AM processes, not necessarily adopting AM process-specific variables. AM design heuristics have shown great potential in creating new designs adapted to AM amongst novice engineers (Blösch-Paidosh and Shea 2021; Blösch-Paidosh and Shea 2019) and have shown indications that they support inspirational discussions in very early ideation amongst experienced engineers (Lindwall and Törlind 2018). While design heuristics focus on early ideation and inspiration, design principles also involve design fundamentals and process dependent variables (Mani, Jee, and Witherell 2017). In other words, design principles can also be used in mid-stages of the design process, such as detail design (Valjak and Lindwall 2021). Such design principles have been tested amongst various novice and experienced engineers, with promising results in providing support through early phases of the design process (Perez et al. 2019; Lauff et al. 2019). Altogether, these supports can open up opportunities to create a design fully adapted for AM and explore the various AM design potentials for a specific design.

Creating knowledge in design

For an engineer to expand their expertise level and hence their creative abilities, they need to create knowledge in their design practices. A person goes through five steps to create skills and knowledge (Cheetham and Chivers 2005): Novice (step 1); Advanced beginner (step 2); Competent (step 3); Proficient (step 4); and Expert (step 5). Novice learners often follow the rules and guidelines, while experts do not rely on such supports (ibid.). However, expert engineers tend to use various design strategies, that novice engineers do not have the same knowledge or understanding of yet (Ahmed, Wallace, and Blessing 2003). Design teams are often diverse, with various knowledge base levels amongst individuals in various areas. There is a need for engineers to exchange knowledge with each other, support each other in developing new skills, and increase the total knowledge within the design team (Mamykina, Candy, and Edmonds 2002). As novice learners in a certain area, engineers often need to approach design problems using a 'trial and error' approach (Ahmed, Wallace, and Blessing 2003). Therefore, it is important to have an open environment where engineers feel that they can make mistakes while learning (Dostaler 2010; Mamykina, Candy, and Edmonds 2002). Additionally, it is suggested that engineers going through the first steps of creating knowledge need to have engaged design coaches to fully understand the new aspects of design (Dym et al. 2005).

Prabhu et al. (2022a) suggests that it is important to introduce opportunistic DfAM methods early in the learning process, and the ability for designers to use DfAM concepts is directed by general engineering expertise. Previous research suggests some areas of importance necessary to gain AM expertise and hence utilise engineers' creative abilities. Hagedorn, Krishnamurty, and Grosse (2018) highlight four knowledge bases of DfAM: *capability, process, machine,* and *product*. Simpson (2020) presents an AM readiness model, focusing on *machine, material, design,* and *people*. In this paper, three **AM knowledge domains** have been used as a basis for analysis, derived from both the four dimensions in Simpson's (2020) AM readiness model and Hagedorn, Krishnamurty, and Grosse (2018) four knowledge bases. This study focuses on how engineers (people) manage the knowledge domains of *AM material*, *AM machine & process*, and *AM design* while working with AM in their design practices.

Restrictions and creativity

Compared to what engineers are used to when working with conventional manufacturing methods, designing for AM requires them to navigate through various AM-related restrictions to adapt to new possibilities and limitations. Additionally, general restrictions in design need to be considered to fully exploit engineers' creative abilities. Amabile (1998) argues that there are two main resources when considering creativity in a design project: sufficient time and money on a project can either support or kill creativity amongst design teams. A later study concluded that even though time pressure certainly can affect creativity negatively, some people still manage to utilise their creative abilities by having a sense of focus (Amabile et al. 2002). If an engineer were to concentrate on a single task for a large portion of their day, their creativity level would be raised (ibid).

Additionally, it has also been shown that some design process constraints could be used to guide and limit the creative process (Onarheim 2012), hence directing a design task towards a single focus. However, it is important to acknowledge the risk of having design fixation, since this could be present even though designers do not perceive it (Linsey et al. 2010). Design fixation can have a negative impact on creativity related to DfAM (Abdelall, Frank, and Stone 2018a) and a manufacturability software has been designed to assist designers to avoid such design fixation for AM (Abdelall, Frank, and Stone 2018b). While specifically designing in technical industries, a high level of creativity is needed to navigate multiple contradictory constraints (Eckert et al. 2012). For engineers to maintain a creative drive in a restrictive setting, there should be flexibility in involving constraints, which are dynamically added and removed throughout the design process (Onarheim 2012). This is in line with what Laverne et al. (2015) and Floriane et al. (2017) highlight, that giving engineers the necessary AM knowledge needed will influence their creative process. They suggest that too much information at once can hinder engineers in utilising their full capability (ibid.) and hence their use of their creative abilities. Engineers need to have extensive knowledge of AM and insights on future opportunities to take significant steps in using their creative abilities (Taura and Nagai 2017). In summary, for engineers to fully explore their creative abilities, they need to have clearly **specified goals** (Amabile 1998), **time** to be focused on a specific design task (Amabile and Hadley 2002), **understanding** of the design problem (Eckert et al. 2012), **flexibility** to move around design constraints (Onarheim 2012), and **cognitive possibilities** to see the potential of designs in society (Taura and Nagai 2017).

Research design

Case studies have a highly recognised value in explorative studies since they can offer rich information and can clarify poorly understood aspects in processes (Yin 2014). In exploring how engineers explore AM design potentials in their designs and their design process, a case study approach is used to better understand such phenomenon. Based on three product design cases, this study has been designed as a collaborative workshop series, which includes three case companies operating in the space industry (Table 1) and researchers from two universities.

All three case companies operate in the highly regulated space industry and were selected for their intent to explore the possibilities of using AM as the end-use manufacturing method for a specific product. Studying these three companies allowed the allowed the observation of a new manufacturing technology, which is considered to increase the possibility for engineers to be creative while working in a highly regulated (and often conservative) industry. The study, therefore, provides valuable insights for the design community about the implementation of AM in companies' design processes. The case studies used in this study should be seen as illustrations of examples from the industry that have approached the phenomenon rather than generalisable results (Guthrie 2010). A presentation of the three product design cases can be seen in Table 2. All three companies started from an already existing product family with the intention to re-design for AM.

Table 1. Descriptions of the case companies.

Company	Company Description	Number of employees
A	The company operates in multiple segments of the aerospace industry. The studied part provides products for in-orbit applications with responsibilities that span the entire chain from R&D to sales for several product areas.	1400
B	The company develops satellites and subsystems for the commercial and ESA markets. The studied part has the responsibility of design and assembly of different satellite subsystems as well as mission analysis.	2900
C	The company is developing complex and high-performance components for aerospace. The studied part focuses on product development and manufacturing of subsystem components for civil aircraft engines and launcher applications.	18,000

Table 2. An overview of design cases.

Case	Original design description	The initial status of the case
A	A satellite antenna for receiving or transmitting radio frequency waves (signals) to transfer information through its internal geometry. The antenna needs to endure both a launch and the space environment implying high demands on fulfilling technical requirements.	Entering the study with an idea to re-design an existing product for AM. Reasons to investigate AM are potentials for: reduced machining cost and lead times, more flexibility in design, reduced handling and assembly needs through fewer parts, reduced mass, and increased design freedom.
B	A propellant flow distributor for a satellite propulsion system with one input and five outputs. The number of outputs implies the most complicated product version (the simplest version is one input and one output).	Entering the study with an idea to re-design an existing product for AM. Reasons to investigate AM are potentials for: reduced cost, reduced lead time, an optimised design concerning the system rather than manufacturing machine capabilities, and reduced mass.
C	A manifold for a rocket engine turbine, containing high pressure and temperature gas and directing and distributing the gas towards the turbine rotor. To achieve the high performance of the turbine, pressure losses should be as small as possible within the manifold.	Entering the study with a re-designed product for AM that had gone through two design iterations. Reasons to investigate AM are potentials for: part integration and optimised (complex) geometry, integrated cooling, and reduced cost.

Design for AM workshops

Seven collaborative workshops were performed over 21 months between September 2017 and April 2019, spanning from ideation and inspiration to evaluation, providing an opportunity to collect data along a design process (Figure 1). While designing the workshop series, the case companies expressed a wish to have a focus on learning and understanding the opportunities and limitations offered by AM. Therefore, the workshops were initially designed to include AM design potentials through design heuristics and design guidelines (described by e.g. Blösch-Paidosh and Shea 2021; Allison, Sharpe, and Seepersad 2019). This is in line with the notion that novice learners need to follow rules and guidelines (Cheetham and Chivers 2005). Throughout the workshop series the focus continued to be on creating knowledge and expertise regarding AM in design. This was made through a learning-by-doing approach (Ahmed, Wallace, and Blessing 2003), allowing participants to explore the potential of AM in their designs through prototyping and testing. Overall, the workshops were mainly designed to be open-ended to allow participants to direct what activities needed to be made throughout the series.

Five workshops were originally planned, but two additional workshops were added during the process due to a noticeable need. Table 3 shows an information overview of the conducted workshops. The original five workshops were designed to support the case companies to involve AM in design (ideation and inspiration, conceptualisation, definition, verification, evaluation). The workshops focused on joint teamwork to bring new insights between the cases, and in between workshops the cases continued their internal work. After the first workshop, participants asked for an additional workshop, focusing on DfAM with an academic expert not involved in the academic team. The workshop involved economic aspects, topology optimisation, and the AM process including layer thickness and post-processing. This allowed them to gain more knowledge, understanding and experience of AM (AM expertise). Later in the workshop series, academic partners asked for the second additional workshop, focusing on presenting and involving approaches that had been developed. Both additional workshops brought further insights on the design

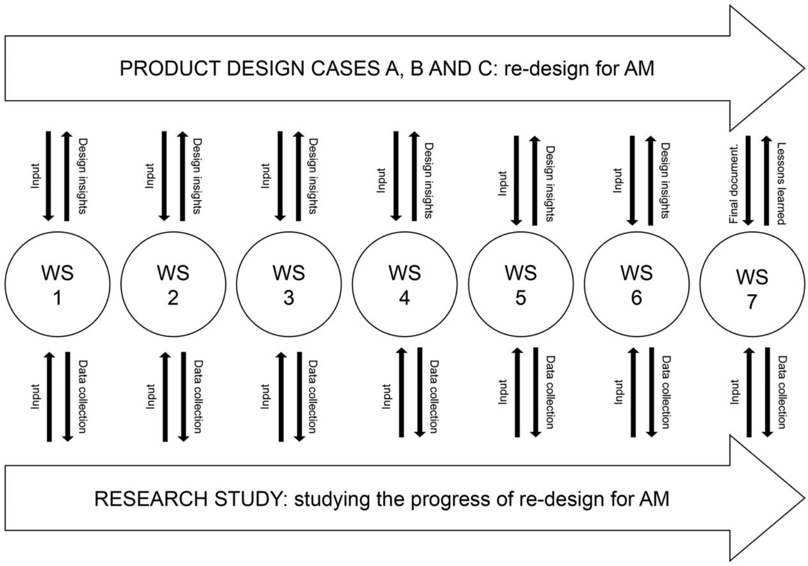

Figure 1. Workshop design overview.

progress and added more data for the research studies. All original workshops were performed during a lunch-to-lunch meeting.

The case companies and academic partners both provided input for each workshop. The case companies continuously presented the status of their design progress with illustrations, evaluations, lessons learned and the current issues they were facing. The academic partners provided knowledge and support regarding AM in design, for example, through design heuristics for AM or prototyping guidance. The cross-company workshop approach also meant that the participating engineers gained design insights from discussions with engineers from other companies. The three cases had specific company interests, but the common interest was (in the first workshop) stated as gaining knowledge and understanding of DfAM. For this study, the profound focuses of each workshop contributed to the overall understanding of the progress of designing for AM from a creativity perspective.

Workshop 1 – inspiration and ideation

The first joint workshop was designed to support engineers with inspiration and ideation regarding AM in design. The researchers presented a set of 10 design heuristics specified for AM, gathered from literature (e.g. Leary et al. 2014; Gao et al. 2015; Gibson, Rosen, and Stucker 2015; Yang and Zhao 2015; Song et al. 2015; Thompson et al. 2016; Blösch-Paidosh and Shea 2017). The purpose was to support ideation activities in the workshop, and the companies brought their original product design case descriptions together with initial issues they faced when embarking on the progress of re-designing for AM. After the presentation of design heuristics, examples of AM designs from the industry and the original design cases, joint discussions, and creative activities such as black-box-compositions followed. The intention was to raise new design insights for continued design activities for each case. A summary of the heuristics and the outcome of the first workshop have been presented in (Lindwall & Törlind, 2018).

Table 3. Information overview of workshop series.

WS	Focus	Original/Additional WS	Joint/individual	Activities and input	Duration
1	Inspiration and ideation	Original	Joint WS	• ideation exercises for each use-case • Presenting ten design heuristics (e.g. integrated design, embedded joints, and anisotropic materials) • Presenting design examples in the space industry	One and a half day
2	Design for additive manufacturing	Additional	Joint WS	• DfAM exercises with an DfAM expert	One day
3	Conceptualisation and AM design uncertainties	Original	Joint WS	• design progress presentations • identifying main issues that the cases were facing regarding the AM process and design practices • presentation of initial AM design framework characteristics	One day
4	Prototyping preparations	Additional	Individual WS with each case	• design progress presentations • exploring how to involve prototypes in the design process to evaluate AM design uncertainties encountered for each case • presentation of refined AM framework	Two to four hours
5	Definition, prototyping and new AM design uncertainties	Original	Joint WS	• design progress presentations • AM process and material evaluations • involving prototypes in the design process to evaluate AM design uncertainties encountered for each case • presentation of refined AM framework	One day
6	Verification and the AM re-design progress	Original	Joint WS	• design progress presentations • prototyping and testing regarding both AM process and material-dependent variables	One day
7	Evaluation	Original	Joint WS	• design progress presentations • evaluating the design progress • discussion on lessons learned and future research	One day

Workshop 2 – design for additive manufacturing

The second joint workshop was an additional workshop that engineers asked for during the first workshop. It included an expert on design for AM to enable engineers to learn more about DfAM and its various perspectives, such as economic aspects, supply chain implications, topology optimisation and post-processing. The researchers mostly observed and participated in the workshop, rather than facilitated it. As an output from the workshop, the engineers acquired new AM design knowledge and design insights for their specific cases.

Workshop 3 – conceptualisation and AM design uncertainties

The third joint workshop had the main focus on the AM design uncertainties the cases were currently facing (in December 2017). AM design uncertainties are in this paper referring to the main unknown aspects that each case was facing regarding the AM process and design. A summary of how the case companies addressed their uncertainties throughout these workshops is presented in (Dordlofva & Törlind, 2020).

Workshop 4 – prototyping preparations

The fourth workshop was the other additional workshop, which was added because researchers saw a need amongst the engineers and cases. This workshop was made individually with each case company and focused on how to involve prototypes in the design process to evaluate AM design uncertainties encountered for each case. The researchers presented a model of how to structure this process, focusing on evaluating the most critical AM design uncertainties for each individual case. It was also an opportunity for the researchers to understand the design process practiced at each company. The design process with prototypes (AM design framework) was further refined during the study and the final version is presented in (Dordlofva & Törlind, 2020).

Workshop 5 – definition, prototyping, and new AM design uncertainties

The fifth joint workshop focused on prototyping and understanding uncertainties that were critical for a suitable design for each case. Before the workshop, the companies had defined (and printed for case C) prototypes to be used for AM process and material evaluations as a step towards understanding the chosen AM process regarding their specific design needs. New issues and uncertainties were raised. The design process with prototypes was further refined during the study and the final version is presented in (Dordlofva & Törlind, 2020).

Workshop 6 – verification and the AM re-design progress

The sixth joint workshop was mainly designed to update the current case progress, including prototyping with a focus on continued uncertainties of the design. At the time (September 2018), prototyping and testing regarding both AM process and material-dependent variables were of the highest interest. Evaluations relating the designs to previously specified uncertainties were made, and current unsolved and new uncertainties were specified.

Workshop 7 – evaluation

The seventh and final joint workshop focused on evaluating the design progress, the workshop series and highlighting lessons learned. The uncertainties of each design case and newly raised challenges were highlighted and reflected upon for the future. All three cases had, to various extent, re-designed their product to be adapted to AM.

Data collection and analysis

Data collection were gathered at each workshop throughout the 21 months: case descriptions, case progress documents, case presentations, observations and taking notes. At least two authors were present at each workshop, where they took notes that afterwards were merged into a final document, which included some direct quotes from engineers. Each researcher had different observer roles (Guthrie 2010) during the workshop. This involved either participant observation, where the researcher participated in workshop activities, or doing non-participant observation, with no participation in the workshop activities.

In addition to the written notes, the final documents included pictures, sketches and post-it notes from the specific workshop, all to cover the progress of re-designing a product for AM and specifying restrictions, challenges and issues. The final workshop also included a short survey on lessons learned. Even if the workshops had diverse focuses along with the design progress, the common interest was to understand and evaluate each company's challenges and limitations. Therefore, the collected documentation brings a coherent understanding of how such restrictions affected the design practices.

The collected data were analysed through three steps; *data condensation*, *data display* and *conclusion drawing* (Miles, Huberman, and Saldaña 2014). Data condensation consisted of extracting data of the design progress, focusing on the AM design potentials and the various restrictions included in each case. For the analysis, AM design potentials included design guidelines, design heuristics and design principles from literature. Data display included illustrations of each case product progress, with AM design potentials in the centre and tables showing design and case setting restrictions related to the major design choices. During the final step of conclusion drawing, the extracted data from three cases were compared and enabled triangulation of the findings, allowing cross-case comparisons (Yin 2014). Using multiple data collection methods and having multiple researchers involved in the documentation to further ensured data triangulation (Creswell 2014).

Case study findings

The three cases are presented to exemplify various *restrictions* that engineers face when learning about AM design potentials through the re-design of a product for AM, particularly in the context of a regulated industry. Table 4 summarises the restrictions that each case highlighted as their challenges while re-designing for AM throughout the workshop series.

Table 4. A summary of restrictions in relation to each case.

	Common restrictions	Case-specific restrictions
Case A	Material data, AM process variation, machine parameters, surface finish, customer requirements	Material certificates, geometrical complexities, case-specific design aspects (e.g. waveguide performance due to as-built surfaces)
Case B		Qualification (product, process and material), case-specific design aspects (e.g. weldability for system interfaces)
Case C		Geometrical complexities, surface finish (as-built and removed support material), Non-Destructive Testing (NDT) methods, case-specific design aspects (e.g. unsupported overhang areas in a closed geometry)

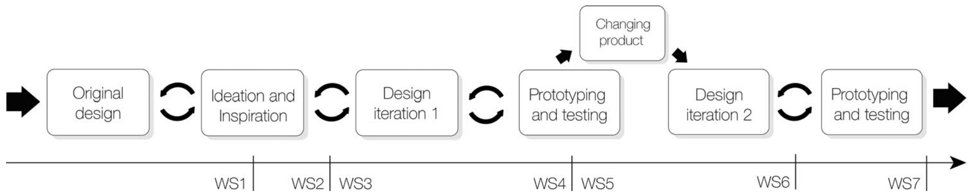

Figure 2. Overview design progress for Case A.

Case A – satellite antenna

During the 21 months of being studied, Case A went through eight main steps (Figure 2), starting with evaluating their original design and ending with prototyping and testing. Throughout the first part of the re-design progress, they mainly explored the possibilities of printing the product in fewer parts. They performed topology optimisation on one part of the product, and also evaluated the impact of surface roughness on product performance; could they even use the as-printed surface internally in the channels? Many design explorations were linked to restrictions specified in Table 4, especially the case-specific restrictions. However, approximately halfway through the workshop series, and after trying to replicate the design with some adaptations to AM, they realised the product was not suitable for AM. They concluded that another similar product was more suitable. However, a significant portion of work regarding design and testing from the first design iteration and prototyping with the initial product could also be used for the new product. Therefore, they gathered and brought their lessons learned into a new round of design iteration, where the newly chosen product was evaluated regarding re-design for AM. Lastly, assessments of the internal design of channels in relation to product performance was made in a final round of part prototyping and testing.

Case B – satellite propulsion flow distributor

Case B took four main steps in their design process during the study (Figure 3), starting with their original design and ending with prototyping and testing. Throughout the study, case B mainly explored internal design alterations for product performance to optimise product functions to AM process capabilities. Since a considerably large part of the interfaces of the product system was set, engineers working with this case had quite strict delimitations in the design. For example, one big issue that case B had to focus on was evaluations of weldability of printed parts due to customer requirements. These evaluations were made due to the customer requirement that the product had to be welded to interfaces in the product system. Therefore, in the final steps of the study, prototypes of the pipes were printed to assess weldability. Like case A, case B mainly explored design potentials related to their case-specific restrictions, specified in Table 4.

Case C – rocket engine manifold

Before entering this study, Case C had already made initial design iterations towards AM. For example, adoptions had been made for AM process limitations such as avoiding internal support structures. Therefore, Case C entered the study with insights from a second

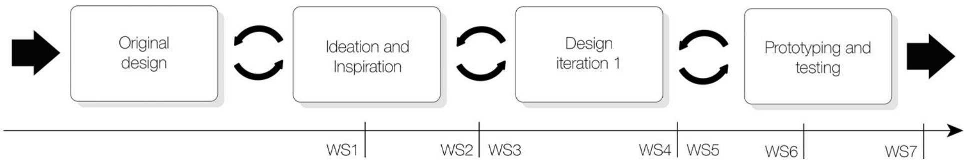

Figure 3. Overview design process Case B.

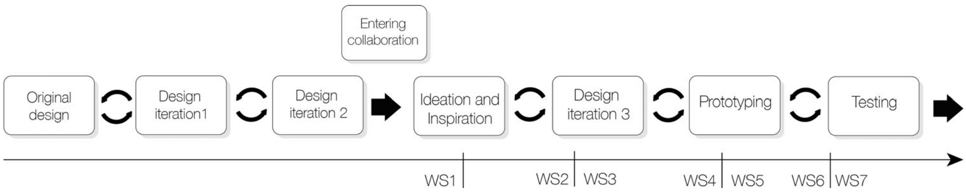

Figure 4. Overview design process Case C.

design iteration and had a total of five main steps (Figure 4), starting with an initial adaption of a design for AM and ending with component testing. Additionally, Case C explored ways to reduce the use of support structures and successfully remove such support material and finally process the surface in places where it was needed. Many of the design explorations made in the design progress during this study aimed to solve case-specific restrictions and several prototypes were printed for evaluation to test the AM design. The design was printed in plastic and metallic printers to evaluate geometrical, material, and functional complexities. These prototypes were used to learn more about both the process as well as exploring the AM supplier's capabilities. Finally, testing to gain a better material understanding and evaluating product performance was made at the end of the study. However, they were bound to the mindset of designing for inspection, to ensure safety standards, which resulted in further limitations in design. Once again, it was the case-specific restrictions that directed the design progress.

Creating AM expertise

The three knowledge domains derived from Simpson (2020) and Hagedorn, Krishnamurty, and Grosse (2018), i.e. *AM material*, *AM machine & process*, and *AM design*, can also be seen in the presented case studies. Additionally, another important factor was found in our three cases, namely that each case had its own *case-specific design aspects* that needed to be addressed throughout the design process while creating AM expertise. Restrictions related to case-specific design aspects direct the exploration of each AM knowledge domain to enable engineers to create an AM expertise. Figure 5 shows a schematic overview of how restrictions with case-specific design aspects relate to addressing restrictions of *AM material*, *AM machine & process*, and *AM design* and how they are connected to creating AM expertise. To understand how restrictions were connected to each domain, data are displayed in Table 5.

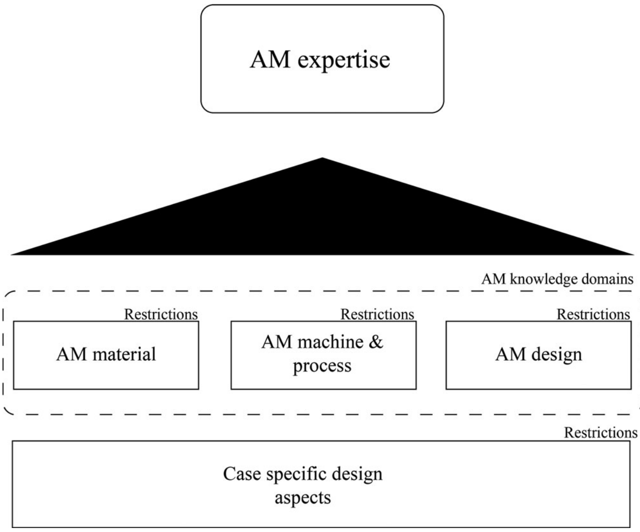

Figure 5. Schematic overview of AM knowledge domains that influence individuals while creating AM expertise.

Table 5. Data display for restrictions affecting engineers to create AM expertise.

Case-specific design aspects	Knowledge domain for AM expertise	Restrictions (i.e. regulations and limitations)
Industry: e.g. financing, 'new space', industry regulations	AM material	• Lack of material data • Understanding new material properties
Company: e.g. airworthiness requirements, time, reseouces	AM machine & process	• Process parameters • Surface finish • Issues with repeatability • Geometrical tolerances • Machine availability • Support materials
Product system: e.g. defined interfaces	AM design	• Part geometry • Qualifying the product • Product performance

AM material

While Cases A & B entered the study with none or limited amount of material data, Case C had already been through two design iterations and started to gain some knowledge in this area. Even though the cases had different challenges and restrictions in relation to *AM material*, this was an area that, early on, showed a need for exploration. Due to the limited material data available at the time, engineers needed to gain such information; when using traditional manufacturing methods they already had access to this information. The lack of material data on AM, and the need to explore this area, resulted in engineers becoming restricted in their opportunities to fully explore AM design potentials for their designs since they had to spend time on this topic. However, to some degree, all three cases focused on exploring material properties through their prototypes and testing phases, once again showing that this is something of great importance while evaluating their designs.

AM machine & process

Another area that was highlighted to be of great importance was the need to learn and understand the chosen *AM machine & process*. All three cases were in contact with different AM suppliers (part manufacturers) and each case used a specific combination of material, AM machine and process. Initially, all three cases saw potential issues with AM process parameters, surface finish, repeatability, and geometrical tolerances. All three cases also stated that they explored *AM machine & process* capabilities during their design iterations and prototyping/testing while optimising product functions, avoiding excessive support materials, and managing necessary support material. Cases A and C highlighted several continued issues that needed to be addressed after the study was finished, such as geometrical tolerances, limiting the need for support materials, and managing the surface finish given by each process.

AM design

The cases mainly raised questions regarding part geometry and qualifying their designs when addressing the various *AM design* aspects. Specific AM design potentials were managed throughout the design iterations through exploring topology optimisation, adapting the design according to product performance, and consolidating the design to have fewer parts. Prototyping and testing were conducted to evaluate AM design aspects as well as functionality and performance of the final design.

Case specific design aspects

All three cases focused on different perspectives of the three knowledge domains, all due to their case-specific restrictions. To some extent, all three cases were constrained by the customer and the product system. The product had pre-defined interfaces that needed to be considered, and customers had product-system specific constraints (i.e. performance measurements). The specific company of each case also had its own set of restrictions in terms of resources (time and budget). Lastly, the industry had a high influence on each case. It was in terms of political decisions (financing in European space exploration), 'the space race' (new incentives in the industry already had AM in their products and/or were pushing it), and industry regulations.

Discussion

When exploring how to include AM in these three cases, *AM materials* and *AM machine & process* aspects were the immediate aspects to explore. Even though the cases mainly focused on these two aspects, *AM design* aspects and case-specific design aspects were highly discussed and present at each stage of the design progress. In our three cases, there were many questions about whether AM would increase or reduce product performance. Especially product performance in relation to material properties and surface finish. Additionally, they explored the possibilities to use non-destructive-testing methods for the AM printed parts. Since the engineers included in our study had extensive knowledge and experience of the case products and product development for traditional manufacturing methods, they are considered to be expert engineers. However, these engineers are put into a situation where they do not have the same amount of information and knowledge about the manufacturing method that they are used to. Even though they are expert engineers, they are forced into taking the steps of a novice or advanced beginner (as described by Cheetham and Chivers 2005) while working with AM.

The three cases aimed to explore how AM could benefit their designs, covering the strive to create innovations, hence utilising their creative abilities. These cases have illustrated the importance to address at least three of the creativity restrictions presented in the theoretical section. Firstly, the cases have been highly flexible while addressing the design constraints (as highlighted by Onarheim 2012), since they have been managing constraints in various perspectives; customer specific, AM specific, and case specific. They have also put in major efforts in understanding the design problem (as suggested by Eckert et al. 2012) and putting in time to focus on the specific design task (as highlighted by Amabile and Hadley 2002). Several restrictions were evident in the cases (presented in Table 4) and influenced how each case explored AM for their design projects. Restrictions, in this paper, are defined as the collection of industry regulations and limitations (design constraints and AM limitations), and we do not address them separately. The expert engineers involved in our cases tended to focus on the two knowledge domains *AM material* and *AM machine & process*. We suggest three main reasons behind an early focus on these two domains. Firstly, material properties are of great importance for both performance and cost measures for the types of products in the case studies. Secondly, expert engineers found themselves in the complex situation of being an expert, but without sufficient information and understanding of these AM knowledge domains. They therefore needed to take the learning path of a novice learner through a 'trial and error' approach (as described in Ahmed, Wallace, and Blessing 2003) to start exploring AM design aspects. This could be a result of mainly focusing on the two knowledge domains of which they are most knowledgeable with regards to traditional manufacturing methods. Thirdly, studying cases working with re-design for AM is another possible reason behind the focus on two of the three knowledge domains. Products in other industries or development of new products could require a higher degree of focus on the AM design domain. Our results suggests that case-specific design aspects directed the learning path that the engineers chose to take within their design case. Restrictions and opportunities associated with case-specific design aspects in relation to their previously novice AM expertise constrained the engineers to one or two of the AM knowledge domains. It is also important to acknowledge the limited amount of available material data and a limited understanding of the AM machine and process due to not having a machine easily accessible. *AM design* aspects cannot be fully addressed until material, machine and process perspectives are explored to a satisfactory level, and hence the big breakthrough solutions might be less obvious. To include AM in design, it is far more complex than 'seeing opportunities and limitations' through AM design heuristics, AM design principles and AM design guidelines if these are not connected to product-specific aspects.

Previous studies suggest that open environments are needed to support engineers in making the necessary mistakes while learning (Dostaler 2010; Mamykina, Candy, and Edmonds 2002), hence supporting creativity. It is therefore also important to support engineers in making mistakes while learning AM. The three cases included in the study were all demonstrator projects, giving designers a freedom to explore AM for their designs. A significant portion of the workshop series focused on 'learning by doing', even though there was a relatively tight time schedule. The workshop series also allowed an open environment between engineers in the three cases, allowing them to discuss each other's problems and ask the 'silly questions' that opened up new thoughts. To support creative outcomes, there is a need to include constraints and restrictions in a dynamic manner when designing (Onarheim 2012). In line with this, Laverne et al. (2015) and Floriane et al. (2017) have highlighted the need to give engineers specific AM knowledge at various stages of the design process when it is needed the most. Our study suggests that expert designers with limited experience of AM need freedom to explore material, process, and machine perspectives before being enforced to deliver final concepts in relation to AM design aspects.

Engineers were attracted to the new design opportunities offered by AM, and had a desire to engage in learning opportunities. However, the complex situation of being expert engineers in design with a lack of sufficient AM knowledge and experience made it hard to know where to start. Engineers needed to use the specific AM guidelines on what they were 'allowed' to do with AM, continuing to be in a 'safe zone' while learning. Having several case-specific restrictions such as industry regulations, company requirements and pre-defined interfaces in the product system directed the learning path as well as the chosen activities for their design practices. Innovating within regulated industries, such as the space industry, can be compared to performing innovation 'in a box', where restrictions (including regulations and limitations) set the boundaries of such a box.

Additionally, to truly explore potential designs for AM, our study shows that the three knowledge domains (AM material, AM machine & process, AM design) need to be included. Working to increase the three knowledge domains of AM expertise (both in terms of theoretical and practical understanding) leads to a higher degree of AM expertise and leads to designers making use of their creative abilities. When organisations want to adopt AM in design, with the ultimate goal to produce innovations, there is a need to assist engineers and design teams to expand their AM expertise and supporting their exploration of the three AM knowledge domains. To exploit their creative abilities while introducing a new technology into their design practices, engineers need to have room for learning that will expand their levels of expertise, especially related to case-specific restrictions. In summary, our study illustrates case-specific restrictions and have identified three knowledge bases, which can be seen in previous literature as well as in the empirical findings.

Conclusions

The relation between restrictions in design and how engineers increase their AM expertise have been explored through three case studies through a series of workshops. The workshops have been designed with the aim to support engineers to fully utilise their creative abilities in design for AM. Our study showed the importance of case specific design aspects (i.e. learnt from testing and prototyping) for increasing expertise. While AM material, machine & process, and design were of importance throughout the design process, it was the case specific issues that directed the learning process. Our study thereby highlights the importance that case-specific experiences have on the engineer's learning path of adopting AM. When exploring the possible design space using AM, there is currently a lack of material data and process understanding compared to traditional manufacturing processes. In all three cases, the engineers showed hesitation while learning and adopting AM, since information on material, machine and process perspectives was not as accessible as they were used to. Engineers find themselves in a complex situation, where they are experts in design of their specific product but lack the in-depth understanding of knowledge domains as they are used to having. They are attracted by the new design opportunities offered by AM, and at the same time are novices of the manufacturing method. This implies a potential conflict for engineers; should they remain in the 'safe zone' using traditional manufacturing, or create innovative solutions and accept more uncertainty? Hence, this article highlights the conflict between either being 'safe' or being innovative, when innovation in regulated industries is compared to taking place 'in a box'.

Implications for theory and practice

Findings from this study show both a theoretical and practical gap. From a theoretical perspective, the study has increased the understanding regarding the implications of restrictions on creating AM expertise amongst engineers. Additionally, from a practical perspective, our study highlights important areas that need to be considered while supporting engineers to fully exploit their creative abilities.

Limitations and future work

The study presented in this paper has been limited to design within the highly regulated space industry. The three cases included in the study all entered the workshop series with the intentions to limit their explorations to metal powder bed fusion (PBF) processes. This was due to the organisational interests and goals related to the specific design cases. Further research including all AM processes should also be conducted. Additionally, engineers included in the study had limited experience in designing for AM. Future research should also include engineers that have design for AM experience to explore if case-specific design aspects direct the designs as strongly as this study indicates. Future research should also include cases in less regulated industries to see if restrictions are of as great importance while creating AM expertise. Additionally, this study has been focused on *AM expertise* in relation to creativity in design for additive manufacturing. Future research should also include *AM motivation* and *AM creative thinking skills* to support engineers to fully exploit their creative abilities while adopting AM in design.

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