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# A risk analysis method for implementation of additive manufacturing

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## ABSTRACT

The evolution of additive manufacturing (AM) over the past few decades has significantly shifted its application from prototyping to the production of final products. Despite this progress, the industrial uptake of AM remains limited due to the complex integration challenges within existing manufacturing value chains. This paper addresses the gap by presenting a prescriptive approach for assessing risks associated with incorporating AM into established workflows. Utilising two case studies from the 'Demonstration of Infrastructure for Digitalization enabling industrialisation of AM (DiDAM)' project, which involves several Swedish manufacturing companies, this study develops a methodology for risk assessment. The proposed method involves mapping workflows into multi-domain matrices, establishing dependencies with uncertainty values, and performing risk analysis to determine potential impacts. Results indicate that this quantitative risk assessment approach provides valuable insights into hidden issues that could affect the implementation of AM. By offering a decision-support tool for managers, this methodology enhances the likelihood of successful integration of AM and supports digitalisation efforts in traditional manufacturing settings. The practical applications of this approach are demonstrated through a detailed analysis of the two industrial cases.

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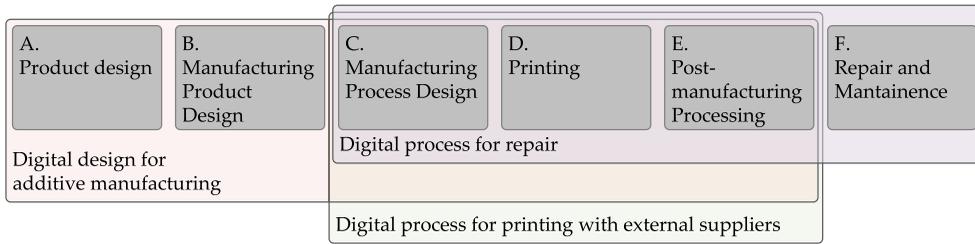
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## 1. Introduction

Significant research and development resources have been put into additive manufacturing (AM) in the past few decades, particularly focussing on new materials and manufacturing processes (Huang et al. 2015). Among various reasons, new manufacturing paradigms such as Industry 4.0 have led to significant shifts in how companies perceive manufacturing value chains with newer technologies such as AM, playing a central role in them (Alc cer and Cruz-Machado 2019).

With the maturity of the technology, its use has moved significantly from prototyping to manufacturing of final products (Thompson et al. 2016). However, previous studies show that there is still a significant gap in its industrial uptake (Kulkarni et al. 2021; Martinsuo and Luomaranta 2018). One reason often mentioned is the lack of research to review its position in the overall product and process cycles (Mallalieu et al. 2022; Martinsuo

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**Figure 1.** The generic AM workflow and the demonstrator cases coverage mapped onto it. Reproduced from Isaksson et al. (2024) under CC BY-NC 4.0 Licence.

and Luomaranta 2018). Studies indicate that while the opportunities of additive manufacturing, such as design flexibility, enhanced product complexity, and customisation are clear, companies often face challenges in adapting their existing value chains to integrate AM effectively (Isaksson et al. 2024; Mallalieu et al. 2022). Digital aspects of implementing AM, such as design, workflow and simulation often create risks, which inhibits its full integration in the industrial eco-system (Mallalieu et al. 2022). The problem is further amplified for companies with a well-established portfolio of traditional manufacturing methods (Hajali et al. 2023). Incorporating AM without prior analysis of the risks can lead to major disruptions to existing workflows.

Existing studies have identified these challenges, but the literature remains largely qualitative, lacking structured, empirical approaches to systematically evaluate and quantify these risks. This paper addresses this gap by introducing a prescriptive approach for risk assessment in adoption of AM. Unlike prior studies that primarily describe challenges, this approach provides a structured framework for collecting empirical data and conducting quantified risk analyses. The objective of this paper is therefore to propose a prescriptive approach which can assess such challenges, and understand the risks to mitigate them. The paper derives from two case studies from a long-running project called 'Demonstration of Infrastructure for Digitalization enabling industrialisation of AM (DiDAM)', concentrating on the digital value chain analyses of AM in several Swedish manufacturing companies. The project involved three 'test beds' based on a generic AM process flow as shown in Figure 1. In this paper, we consider two out of the three test beds, as the third case, Digital Process for Repair, is out of scope for the topic of this paper. The paper presents a methodology for risk assessment for companies looking for successful implementation of AM in their value chain. By applying the proposed methodology across different industrial settings, we demonstrate its applicability and potential for generalisation. The findings contribute not only to bridging the gap between the potential of AM and its industrial uptake but also to providing decision-makers with actionable insights to mitigate risks and facilitate smoother integration into existing workflows.

## 2. Background

AM, which finds its origins as a method for rapid prototyping, has gained significant traction in the last few decades. A study by the European Patent Office, for instance, estimated a compound annual growth rate of +26% between 2013 and 2020, based on an analysis of published patents during that period (Cavallo et al. 2023). The annually published Wohlers

report of 2023 also shows a significant growth of the market size, with revenues estimated to have grown from USD 6.1 billion in 2016 to USD 18.0 billion in 2022 (Campbell et al. 2023), which, however, includes both products and services. The growth is often attributed to two main factors: first, the expiration of founding patents in the 1980s and 1990s, which led to a significant rise in low-cost fabrication equipment (Beaman, Bourell, and Wallace 2014). Second, the rapid movement in technology enabled by digitalisation has led to new business opportunities and value chains (Merrill 2014). As the technology has matured in the past few years, significant challenges have however emerged, which have hampered its widespread adoption in the industry. Thomas-Seale et al. (2018) for instance, refer to numerous reports from the UK which highlight many challenges associated with adoption of AM – including, but not limited to – sustainability, organisational complexity and so on (Faludi et al. 2015; Ford and Despeisse 2016).

A number of studies have discussed these challenges in detail (Ahuja, Karg, and Schmidt 2015; Ituarte, Khajavi, and Partanen 2016; Mellor, Hao, and Zhang 2014; Omidvarkarjan et al. 2023). The following section presents a brief overview. To align with the focus of this paper, the scope of the review and the case studies were restricted to the digitalisation and implementation aspects of AM, and technical aspects of material science and the printing process are kept out of scope.

### **2.1. Product development related challenges**

The field of design for additive manufacturing (DfAM) has been extensively studied to establish guidelines for optimising designs using AM technologies (Diegel, Nordin, and Motte 2019). AM offers unique design possibilities not typically found in traditional manufacturing, presenting both opportunities and challenges (Mellor, Hao, and Zhang 2014). One major challenge is shifting from conventional manufacturing constraints to those tailored for AM (Borgue et al. 2019). This shift can be difficult due to the high costs associated with testing and certification, as well as scepticism towards new design approaches. Moreover, designers may over-utilise the design freedom offered by AM, which in turn, make the testing and certification extremely expensive or difficult (Borgue et al. 2019). The freedom provided by AM also demands a complete redesign of products traditionally manufactured, leading to significant disruptions in the design process (Hague, Dickens, and Hopkinson 2006). For instance, Birtchnell and Urry (2016) suggests a complete rethink of the conventional information flows within manufacturing systems to fully exploit capabilities offered by AM. On the other hand, research by Rylands et al. (2016) on two companies indicates that AM can create additional value streams, enhancing manufacturing capabilities rather than causing disruption. While diversifying manufacturing processes is advantageous, it also necessitates managing multiple systems and information flows, which can lead to inefficiencies.

Further, while there have been significant advancements in the range of materials available to the designer to choose from, it still remains low (Mellor, Hao, and Zhang 2014). Examples of other constraints the designer may face when working with AM include volume, geometry (Müller, Panarotto, and Isaksson 2021), compliance properties (Doubrovski, Verlinden, and Geraedts 2011) and so on. These trade-offs are often unclear to the designer, making the design process fuzzy with uncertain inputs.

## 2.2. Process-related challenges

Integrating AM into a company's design and production processes requires substantial digital transformation. In comparison to traditional manufacturing, process chains involved in AM, both physical and digital are different (Luomaranta and Martinsuo 2022). Zimmermann et al. (2023), for example, compare generalised process chains for AM and conventional subtractive methods and state a number of differences. Apart from the product development-related changes discussed in Section 2.1, the value chain differs because of large divergences in pre-process, in-process, post-process and finishing steps. For instance, in the pre-processing stage, the tool-less nature of AM, its difference in machine preparation, and digital production planning all have implications on the process chain.

Further, there could be challenges based on interoperability needs (Belkadi et al. 2018). Major portions of the design process depend on digital process chains with various software and simulation tools working in sync. Companies may have well-established digital chains, integrating AM into existing digital infrastructure may be challenging. Panfili (2019) highlights that AM-led product development often involves entirely digital workflows, from CAD design interfacing with PLM software to direct printer interaction. AM having a different value chain may therefore also indirectly affect standardisation, certification (Borgue et al. 2019), traceability, quality assurance and quality control (Al-Meslemi, Anwer, and Mathieu 2018; Luomaranta and Martinsuo 2022). Furthermore, companies may incorporate digital twins in their production workflows for monitoring, predictive maintenance, and quality control (Aheleroff et al. 2021), which may not be the case for products produced conventionally.

Finally, there are challenges related to value chains which expand outside the design process but can have a significant influence on the design outcome. For example, designers may consider the supply chain design when architecting a product (Ulrich and Eppinger 2016). It often involves rethinking procurement, logistics, and inventory management strategies to account for the just-in-time nature of AM production and the diversity of materials and technologies used. While AM enables consolidating functions often resulting in more integral products, it may lead to significant change in a company's existing supply chain design, leading to unwanted consequences (Eyers et al. 2021). Similarly, trade-offs exist in areas such as product flexibility, adaptability, and reparability, which may be impacted by such part consolidation (Borgue, Panarotto, and Isaksson 2019).

## 2.3. Organisational challenges

Implementing AM in companies presents significant organisational challenges, with technical expertise and training being among the most important (Omidvarkarjan et al. 2023). AM technologies require specialised skills that many current employees may lack, necessitating extensive training programmes or the hiring of personnel with expertise in relevant areas (Chaudhuri et al. 2019; Martinsuo and Luomaranta 2018; Oettmeier and Hofmann 2016). Further, challenges arise when considering the greater ecosystem, which includes suppliers, vendors, sellers and service providers (Omidvarkarjan et al. 2023). Beyond the design or product architecture-related implications on supply chain, other factors which affect AM adoption include the structure of supply chain in terms of location, logistics, resilience and flexibility (Durach, Kurpjuweit, and Wagner 2017).

Beyond technical and operational challenges, companies face significant strategic and cultural barriers when implementing AM. Concerning the strategic aspects, the high initial costs associated with AM equipment and technology can be a major deterrent (Chekurov et al. 2018), especially given the uncertainty surrounding the return on investment (Priyadarshini et al. 2022). Being a relatively new and fast-moving technology, companies also struggle with the lack of necessary cost models (Lawand et al. 2023, 2020), which makes it even more difficult to accurately estimate its value in a company's portfolio. From a cultural perspective, resistance to change from employees and management can slow the adoption of AM (Omidvarkarjan et al. 2023). Klahn et al. (2018) (in, Omidvarkarjan et al. 2023) for instance, classify the reluctance towards AM in technical and personal dimensions and provide a matrix to address them accordingly. They classify the stakeholders into four categories: Sceptics, Promoters, Opposers and Inhibitors, each having a different level in terms of personal reservations and their perception of the value AM holds for their organisation. Researchers also point out that the size of the organisation is a major factor in the implementation of AM. Mellor, Hao, and Zhang (2014) for instance, explain that small and medium-sized enterprises (SMEs) and large corporations cannot be compared or considered scaled versions of each other. Consequently, the strategies to adopt AM may be completely different depending on the organisational structure and situation (Shah and Mattiuzza 2018).

#### **2.4. Regulatory challenges**

One of the key challenges repeatedly discussed in the literature on the adoption of AM is the lack of standardised regulations and guidelines across different regions and industries (Ronchini, Moretto, and Caniato 2023; Zimmermann, Lentz, and Werner 2019). AM technologies, such as 3D printing, can produce parts with intricate geometries and properties that differ from traditionally manufactured components. This variability makes it difficult for regulatory bodies to establish comprehensive standards that ensure consistency and reliability. For instance, in industries such as aerospace (Wagner and Walton 2016) and medical devices (Horst, McDonald, and Hutmacher 2019), where safety and performance are critical, regulatory bodies have stringent requirements. Lack of specific frameworks for AM can, therefore, cause delays and uncertainties for companies looking to integrate these technologies into their production processes.

Furthermore, the verification and validation processes for AM parts pose another significant barrier. Traditional manufacturing processes have well-established methods for testing and quality assurance, but AM requires new approaches due to its unique production methods (Borgue, Panarotto, and Isaksson 2022; Chen et al. 2021). Non-destructive testing (NDT) techniques and in-process monitoring systems are being developed to address these needs, but they are not yet universally accepted or implemented (Lu and Wong 2017). This lack of standardised testing protocols can lead to inconsistent product quality, which in turn affects regulatory approval. Companies must invest in extensive research and development to meet these evolving standards, which can be costly and time-consuming (Priyadarshini et al. 2022). Moreover, the certification processes for AM parts often require comprehensive documentation and traceability (Ahuja, Karg, and Schmidt 2015), adding further complexity to the regulatory compliance landscape.

In addition to the regulatory hurdles relating to part quality, intellectual property (IP) concerns present another layer of regulatory challenge for the adoption of AM. The ease of digital replication and distribution of designs in AM raises significant issues regarding IP protection and enforcement (Kurfess and Cass 2014). Companies are wary of sharing their digital designs due to the risk of unauthorised reproduction, which could lead to potential revenue loss and brand damage (Vogel 2016). Regulatory frameworks are still catching up with the need for robust IP protection mechanisms specific to AM (Ballardini 2018). Ensuring secure data transfer, protecting design files from cyber threats, and developing legal measures to combat IP infringement(s) are essential for fostering confidence in the use of AM technologies. Until these regulatory barriers are adequately addressed, companies may hesitate to fully embrace AM, thereby slowing its widespread adoption.

### **2.5. Sustainability challenges**

One of the many advantages of AM, often discussed over other conventional manufacturing methods, is its sustainability fingerprint. However, like all other cases, it is highly context-dependent (Graziosi et al. 2024). For example, one issue is material waste and recycling. Certain processes still produce substantial waste (Graziosi et al. 2024; Mishra, Negi, and Kar 2023). Support structures and excess powder, particularly in metal and high-performance polymers, often cannot be recycled effectively, leading to material wastage (Graziosi et al. 2024). Moreover, recycling AM materials can be complex due to potential contamination and degradation of material properties, complicating efforts to reuse materials sustainably (Azevedo, CabreraSerrenho, and Allwood 2018; Raabe, Tasan, and Olivetti 2019). Similar issues arise with factors such as energy consumption, material sourcing and supply chain. Companies are often not equipped with the capabilities to consider these trade-offs when deciding on the risks associated with implementing AM. The risks associated with rebound effects must, therefore, be carefully considered (Liao and Cooper 2020).

### **2.6. Risk assessment in the implementation of additive manufacturing (AM)**

To mitigate the aforementioned challenges, companies must assess the risks involved in the adoption of AM in their existing value chains. A few methods exist in the literature which target this problem. First, De Lima et al. (2023) proposed a decision-making method based on the V-model. The authors list 42 criteria against which data from two orthopaedic implant companies are analysed. While the method collects data from companies through interviews, it does not account for inter-criteria dependencies, if any. Further, it also does not account for the uniqueness of a company's current workflow, which plays an important role in the exposure it has to the risks. In another approach, Altubaishe et al. (2019) propose a failure mode and effect analysis (FMEA) approach based on hybrid AHP-PROMETHEE to select the appropriate supplier(s) in a risk-based environment. The method is limited to the supply chain and, therefore does not consider other influencing factors discussed in previous sections which affect risk. Finally, Moreno-Cabezali and Fernandez-Crehuet (2020) propose a fuzzy-logic-based approach where they assess risks for AM R&D projects. The method considers ongoing projects, which therefore assumes that the company has already integrated AM in its value chain. However, some of the criteria used in the risk assessment such

as cybersecurity and intellectual property, training and planning, etc, are also relevant for companies wanting to assess risks of adoption of AM in their manufacturing portfolio.

## 2.7. Summary and research gap

The review of the literature in the previous Sections 2.1 to 2.5, summarised in Table 1, shows that there are numerous factors which may influence the success of the adoption of AM in a company. The factors are summarised as follows:

- IF1: Design requirements and constraints (R&C)
- IF2: Design process chain
- IF3: Digital process chain
- IF4: Product architecture
- IF5: Skill and expertise
- IF6: Supply chain
- IF7: Business strategy
- IF8: Organisational culture
- IF9: Organisational structure
- IF10: Regulations
- IF11: Testing, compliance and verification
- IF12: Intellectual property
- IF13: Environmental Sustainability

To assess the risk of when implementing AM in a company's value chain, these factors must be assessed against a company's current state of workflow. The risk analysis methods available in the literature (described in Section 2.6) either do not consider the company's current workflow or do not account for inter-criteria dependencies. Therefore, there is a gap in the literature which must be addressed. A method which a firm can use to indicate risks vis-a-vis their current workflow can help in deciding ways to mitigate them for a more successful adoption of AM in their value chain.

## 3. Methodology

A method to assess the quantified risks of AM implementation on an existing workflow was developed. The method is shown in Figure 2. The following sections discuss some of the underlying concepts before presenting the detailed method in Section 3.3.

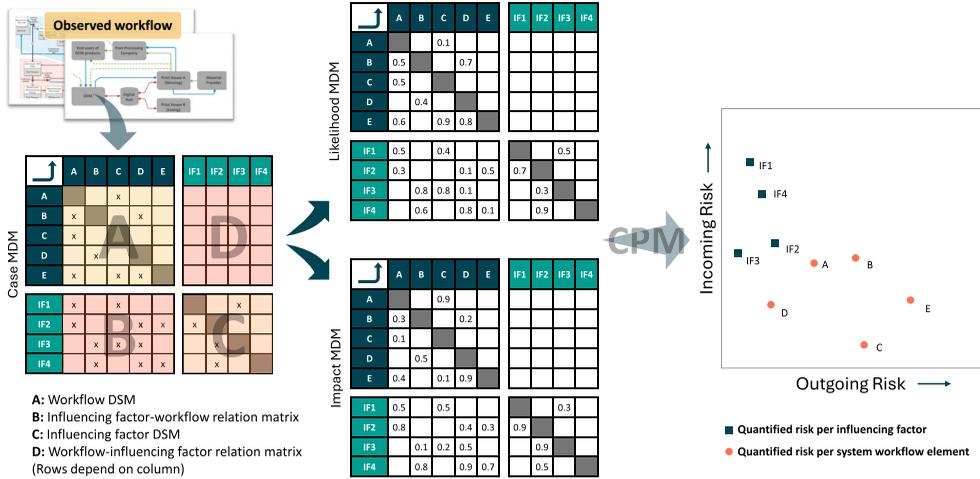
### 3.1. Risk assessment

Engineering systems encounter uncertainties at various stages (Brahma et al. 2023; Earl, Johnson, and Eckert 2005) which manifest as risks such as increased costs or extended project timelines (Grebici, Goh, and McMahon 2008). Risk assessment methods primarily seek to estimate the impact of these uncertainties on key metrics. In engineering systems, there could be many sources of uncertainties both external and internal. Internal sources may include fuzzy requirements, incorrect dependencies etc., whereas external sources of uncertainties may include, unstable supply chain, manufacturing process reliability, or



Chen et al. (2021)										X	X		
Borgue, Panarotto, and Isaksson (2022)	X										X		
Eyers et al. (2021)						X	X						
Luomaranta and Martinsuo (2022)		X	X		X	X							
Priyadarshini et al. (2022)	X	X	X		X		X					X	X
Lawand et al. (2023)	X						X						
Mishra, Negi, and Kar (2023)													X
Omidvarkarjan et al. (2023)	X	X	X		X	X	X	X			X		
Ronchini, Moretto, and Caniato (2023)	X	X			X	X	X	X	X	X	X	X	X
Zimmermann et al. (2023)			X										
Graziosi et al. (2024)	X	X				X							X

IF1: Design requirements and constraints (R&C), IF2: Design process chain, IF3: Digital process chain IF4: Product architecture, IF5: Skill and expertise, IF6: Supply chain, IF7: Business strategy, IF8: Organisational culture, IF9: Organisational structure, IF10: Regulations, IF11: Testing, compliance and verification, IF12: Intellectual property, IF13: Environmental Sustainability.



**Figure 2.** Quantified risk assessment method to assess risk of AM implementation based on the observed or anticipated workflows. The method maps the workflow and influencing factor dependencies in a multi-domain matrix, on which the change prediction method (CPM) algorithm (Clarkson, Simons, and Eckert 2004) is applied to assess risks.

user skill levels (De Weck, Eckert, and Clarkson 2007). Thus, it is crucial to consider these uncertainties and associated risks when evaluating the integration of AM into a company’s existing system.

Classical risk analysis techniques often simplify risk assessment by focussing on individual risks without considering interactions or propagation effects such as FMEA. However, in complex systems these simplifications may not fully capture the real-world complexity of risk networks. For instance, an upstream risk might propagate to multiple downstream risks, leading to a chain reaction or knock-on effect. Further, risks can propagate through interconnected systems or processes.

More recent methods of risk analysis add features such as the propagation of risks through dependencies (Brahma and Wynn 2022). An example of such a method is the CPM by Clarkson, Simons, and Eckert (2004), which was developed to predict the magnitude of risks from design changes propagating in a system. Like many other risk analysis approaches such as fault tree analysis (FTA) and probabilistic risk assessment (PRA) (Mobey and Parker 2002), CPM is also based on the fundamental approach of answering three questions, known as the ‘set of triplets’ (Kaplan and Garrick 1981). These questions are: What can go wrong (failure mode)? How likely is it to occur (likelihood)? What are the consequences (impact)? In CPM, likelihood and impact values are recorded using design structure matrix (DSM), which are processed through an algorithm to calculate the risk to a component from a given change. Additionally, CPM considers the knock-on effect of change, propagating the probability through interconnected components within a system. CPM has also been shown to have certain limitations. Of interest to this article, Hamraz, Caldwell, and Clarkson (2012) argue that CPM does not adequately consider cross-domain risk analysis and therefore suggests improvements on it. This enables cross-domain analysis of systems, which has been used in this paper.

### 3.2. DSM/MDM representation

A popular method of representing dependencies within a system is the use of design structure matrices (DSMs). Introduced by Steward (1981), DSM are square matrices, where rows and columns represent the same set of elements of a system. A mark in the intersections of the rows and columns depicts how the elements depend on each other. While there are many conventions on how to read a DSM, the one followed in this paper is where the elements in the columns initiate the uncertainty, and the rows indicate system elements which receive them. How the marks in the cells are arranged can indicate various characteristics of a system such as task sequences, dependencies or iterations for a task DSM (Wynn and Clarkson 2018; Wynn and Eckert 2017), modularity in product architecture DSM (Browning 2001) and so on.

A modification of the DSM concept, other matrix-based methods include multi-domain matrices (MDMs), which represent dependencies across multiple information domains (Brahma and Wynn 2022). MDMs use a combination of square DSMs and non-square mapping matrices, which can represent other domains (Lindemann, Maurer, and Braun 2009). MDMs are also used in modified CPM approaches, which require risk analysis over multiple domains. Examples of such work can be found in Brahma and Wynn (2022). MDMs are used in this paper to establish the dependencies between the system domain and the domain of factors which influence risk.

### 3.3. Method description

*Observations.* The method, as shown in Figure 2, starts with observations in the concerned company or companies, depending on the setup. The observations primarily aim to capture the workflows and dependencies within their existing system and the anticipated workflow once the AM is introduced.

*Workflow DSM.* The anticipated workflow is then converted into a DSM with dependencies marked at appropriate places between the system elements. This DSM is marked 'A' in Figure 2. The convention used in this DSM is 'Row depends on column'.

*Workflow-influencing factor relations.* The DSM 'A' is then augmented with matrix 'B', which has 13 rows, each corresponding to the 13 influencing factors listed in Section 2.7 and the same number of columns as the corresponding DSM A. Each field in this matrix shows the influencing factor's dependence on the elements of the system as shown in the DSM column headers. Matrix D is a mirror of matrix B, however, the dependencies are reversed i.e. it shows the dependence of the elements of the system workflow on the influencing factors.

*Influencing factor DSM.* The final matrix C is formed by the intersection of matrices B and D. This matrix, is essentially a DSM of the Influencing factors. Marks in this DSM therefore show if any of the influencing factors have influence on each other.

The four matrices A, B, C and D make the overall MDM, which captures the relations between the elements of the system workflow and the influencing factors.

*Likelihood and Impact.* In the next step, the dependencies in the MDM are replaced with likelihood and impact values, which range between 0 and 1. The likelihood is defined as the probability that an uncertainty from one element will affect another. Impact, on the other hand, is defined as the severity effect if such a propagation occurs. For instance, there

may be a 40% probability that an uncertainty in element D may affect element B. Then, the likelihood value entered in the MDM is 0.4 in the corresponding cell. On the other hand, the severity of such an uncertainty propagating from B to D is 50%. Therefore, a value of 0.5 is entered in the impact matrix.

These values of likelihood and impact for DSM A are elicited by interviewing domain experts. The values in matrix A are elicited from experts who have domain knowledge of the system, e.g. company personnel where the new AM workflow is being implemented. Matrices B, C and D's values are elicited by domain experts who have expertise in the implementation of AM.

*Risk prediction using CPM.* In the next step the CPM algorithm (Clarkson, Simons, and Eckert 2004) is applied, with the impact and likelihood MDMs as the input to the algorithm. The CPM algorithm has two parts. In the first step, all possible propagation paths are determined. For example, in the MDM shown in Figure 2, element B depends on A and D, A in turn depends on C, whereas D depends on B. So the propagation paths originating from B can take either of these two paths  $B \rightarrow A \rightarrow C$  or  $B \rightarrow D$ . In the second step, along each such propagation path, the risks are calculated based on the CPM algorithm, where probabilistic operators are used to calculate the combined risk between a set of elements. The combined risk is a sum of the direct and indirect risk, where direct risk is calculated without considering intermediate paths and indirect risk considering intermediate paths between two elements of a system. The CPM algorithm allows for the definition of the number of steps for which the propagation is to be considered. Any number of steps more than 3 or 4 tends to produce asymptotic results.

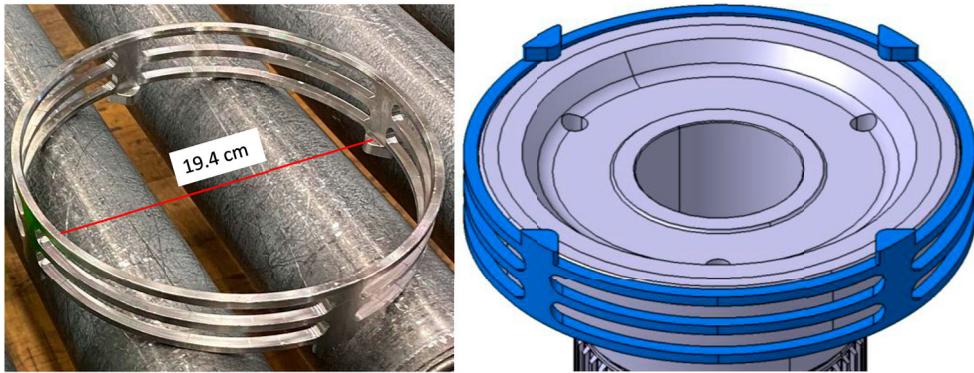
The CPM algorithm results in a combined risk matrix, which is used to generate the combined risk plot as shown on the right side of Figure 2. The values of the plot are row and column averages of the combined risk matrix. The vertical axis shows the incoming risk, i.e. the exposure of each element of the MDM to risks coming from other elements. The horizontal axis shows outgoing risks, i.e. the effect an element has on the others.

## 4. Case studies

The method presented in the previous section is applied to two case studies from a 3-year-long collaborative research project in Sweden, where some of the challenges mentioned in Section 2 were studied in depth. The paper presents the method applied to two cases from different industries and highlights the applicability of the method in two different contexts.

### 4.1. Background of cases

The focus of the project was the value chain disruptions caused by the introduction of AM in various industrial settings. The objectives included identifying the consequently arising needs, with a specific focus on the needs related to the digital aspects. Figure 1 presents a six-step generic AM workflow, which was adopted as the baseline arrangement for the project scope. The steps start with product design (marked in box A) and end with repair and maintenance, as marked in box F. The project was designed to have three 'Test Beds', aiming to study and implement such value chains, thereby advancing the industrial adoption of AM. The motive behind choosing the three test bed demonstrators was (a) coverage of the entire generic AM process and (b) coverage of internal and external aspects of a



**Figure 3.** Gear protector (left) The physical part manufactured by milling (right) The CAD model of the same tool, showing how it surrounds the gear. Reproduced from Hajali et al. (2023) under CC BY-NC-ND 4.0 Licence.

supply chain such as external print houses, traceability, etc, including a special case for repair. Figure 1 shows the three test cases mapped onto the generic workflow.

The application of the methodology presented in the previous section on two of the three test beds is shown below. The scope of this paper was limited to two of the three test beds as it fulfils the objective of showing the applicability of the method in two different cases without unnecessarily increasing the length of the paper.

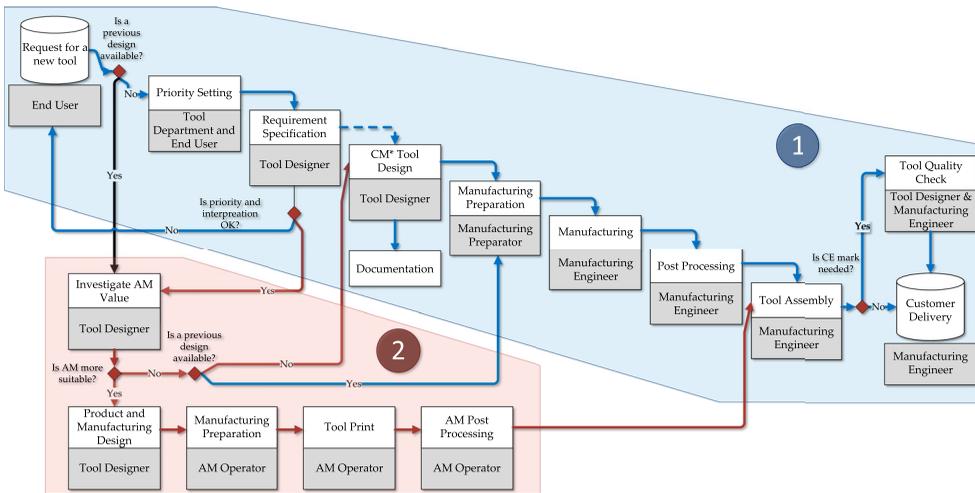
#### **4.2. Case 1: digital design for AM**

The primary objective of this test bed was to showcase the benefits of digital design for AM and to identify procedures for designing tools adapted for AM. The demonstrator use case involved utilising AM to produce tools for the production line of a major Swedish original equipment manufacturer (OEM). These tools are designed for specialised and unique applications in the production line, leading to their manufacture in limited quantities. For instance, Figure 3 illustrates a milled gear protector used to shield a gear during a washing operation. Unlike components for end users, which typically require extensive design time and are produced in large volumes, these tools are characterised by the OEM as necessitating minimal design time and effort.

##### **4.2.1. Case 1: observation method**

The first step in the method application involved understanding the existing workflow in the case company and the changes expected if AM was introduced. A series of interviews, workshops and observational studies were conducted at the 'low-volume design department' of one of the company's plants, with additional study visits to two other plants. The interview participants included design engineers, manufacturing engineers, spare part manufacturers and the end users, i.e. production personnel, who are expected to use the tool in the production line. This provided insights into how requirements and constraints are set and how the design process chain is followed.

Further, a number of interviews and workshops were also conducted to understand the existing AM digital flows. The interviews and the workshops identified the work and



**Figure 4.** Observed workflows for tool manufacturing in a Swedish OEM. Flow marked as 1 relates to conventionally manufactured tools. Flow marked with 2 shows changes due to the introduction of AM. Reproduced from Hajali et al. (2023) under CC BY-NC-ND 4.0 Licence.

information flow. To make the study manageable, a few boundaries were set up for the observations. Consequently, the starting point was decided to be the point where a new tool is requested, whereas the tool’s final delivery to the end-user was determined to be the end-point of the workflow. The work and information flow observed were mapped between these two boundaries, resulting in the workflow shown in Figure 4. Box 1 shows the existing workflow, and Box 2 shows the anticipated modification with the introduction of AM. To test the practicability of the new workflow, three tools were manufactured according to the new workflow, which were previously manufactured by the company by conventional means. The tools were carefully selected based on their current use in the production line and aspects such as suitability to be additively manufactured. Note that it took a few iterations before the anticipated workflow was finalised.

**4.2.2. Case 1: uncertainty elicitation and CPM**

Once the workflow was clearly drawn up, it was converted into an equivalent DSM (Matrix A in Figure 2). Alongside, the other matrices (B, C and D) were also filled up based on the relationships between the elements of the workflow and the influencing factors they may have a dependency on. The quantified likelihood and impact values of the dependencies were elicited alongside the project coordinator. Figure 5 shows the filled MDM, with the fields showing the likelihood values on the top and the impact values on the bottom. Note that matrix D is blank, as the elements of the workflow affect the influencing factor and not the other way around.

Once the uncertainties are elicited, the CPM algorithm is run for three steps, the reason for which is mentioned previously.

**4.2.3. Case 1: results**

The results are presented in two parts. The first Figure 6 shows the resulting MDM, containing the combined risk values. The height of each box shows the combined likelihood and

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	
A: Request for a new tool	0.5				0.5																														
B: Availability of Previous Design - CM	0.5	0.5																																	
C: Priority Setting	0.5	0.5	0.5																																
D: Requirement Specification			0.6	0.6																															
E: Priority and Interpretation			0.7	0.6	0.5																														
F: CM tool design			0.75	0.75	0.75	0.6							0.6																						
G: Documentation				0.6	0.3	0.6	0.6																												
H: Manufacturing Preparation - CM					0.7	0.7	0.7	0.5																											
I: Manufacturing						0.75	0.4	0.75	0.5																										
J: Post Processing - CM							0.75	0.5	0.5																										
K: AM Value Investigation										0.3																									
L: AM suitability											0.3																								
M: Availability of Previous Design AM												0.6	0.5																						
N: Product and Manufacturing Design - AM					0.7	0.8								0.3	0.2					0.7	0.7														
O: Manufacturing Preparation - AM	0.7					0.2									0.7	0.8																			
P: Tool Print	0.8					0.5										0.7	0.7																		
Q: Post Processing - AM																	0.5																		
R: Tool Assembly															0.5																				
S: CE mark requirement																0.5																			
T: Tool Quality Check																	0.7																		
U: Customer Delivery									0.7									0.4																	
V: Design requirements and constraints (R&C)																			0.75	0.4															
W: Design process chain																					0.3														
X: Digital process chain																						0.7													
Y: Product architecture																							0.5												
Z: Skill and expertise	0.7	0.7			0.7	0.7	0.3						0.2	0.7									0.75	0.75											
AA: Intellectual property	0.8	0.8			0.8	0.8	0.8						0.5	0.8									0.8	0.8											
AB: Supply chain	0.8	0.8	0.8		0.8	0.8	0.5						0.7	0.7									0.5	0.5											
AC: Business strategy					0.7	0.7	0.7						0.7	0.7									0.5	0.5											
AD: Organisational culture	0.7				0.8	0.8	0.8						0.8	0.8									0.5	0.5											
AE: Organisational structure	0.7				0.8	0.8	0.8						0.7	0.7									0.5	0.5											
AF: Testing compliance and verification	0.8				0.2	0.2							0.3	0.7									0.7	0.7											
AG: Regulations					0.7	0.5							0.2	0.8									0.5	0.5											
AH: Environmental Sustainability	0.7				0.8	0.8							0.7	0.7									0.8	0.8											

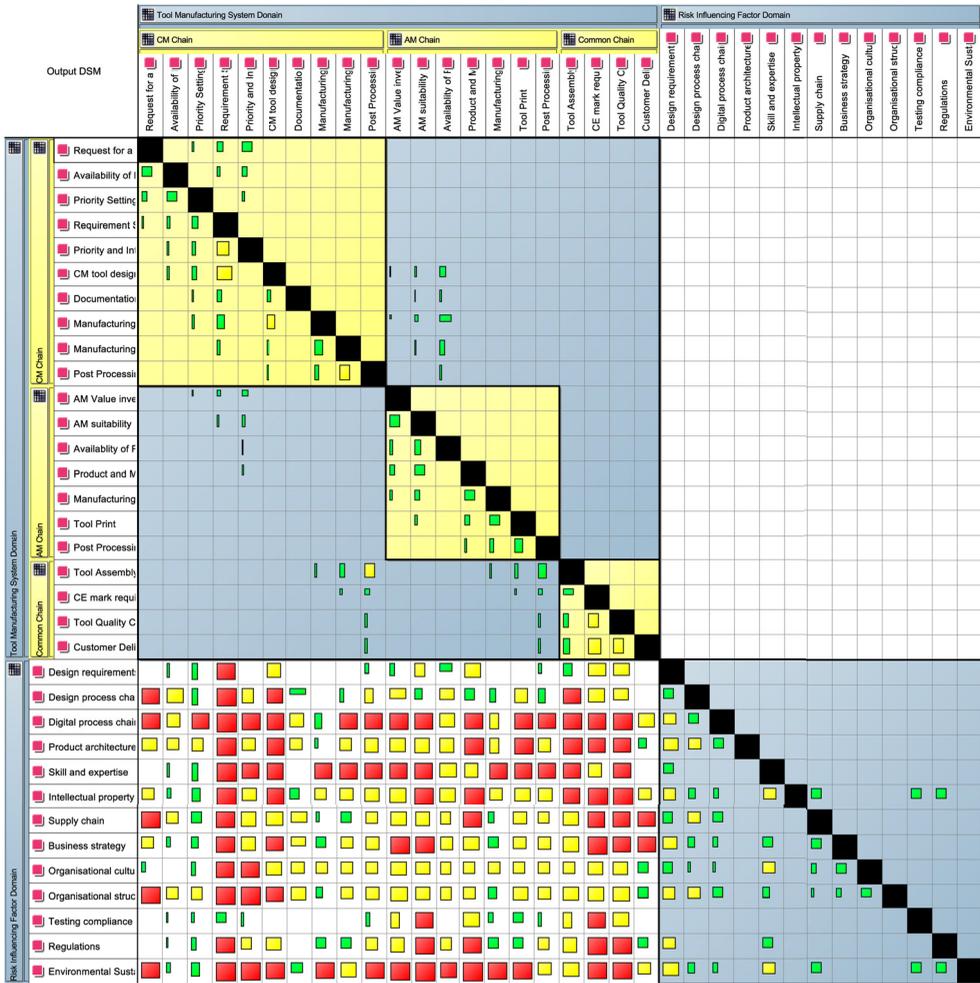
Figure 5. MDM of Case 1. Gray box on the top left shows workflow DSM, grey box at the bottom right is the influencing factor DSM, the remaining two matrices define the relation between the influencing factors and the workflow elements.

the width shows the combined impact. This view, however only shows the element pair interactions, which makes it difficult to discern the risk of each influencing factor because of the system. Figure 7 shows the aggregated results where the row averages of the risk matrix are plotted on the vertical axis and the column averages on the horizontal axis. Of interest are the influencing factors (IF 1 to IF 13), especially their sequence and incoming risk values.

The sequence provides an opportunity to prioritise the risk mitigation and, therefore, is very important. For this case, the risks were calculated as shown in Table 2, also seen in Figure 7. Factor IF 13: Environmental Sustainability has the highest risk, whereas IF 11 and IF 1 are the lowest at 0.13.

### 4.3. Case 2: digital process for printing with external suppliers

This test bed aimed to investigate the factors that support the industrialisation of AM through local print-on-demand production, which occurs close to the end user. Literature suggests numerous advantages of on-demand printing (Ford and Despeisse 2016; Tofail et al. 2018), such as stronger supply chains through alternative production methods, material savings due to less tooling, reduced inventory, reduced transportation needs, and shorter lead times due to simplified manufacturing steps. However, it also poses multiple

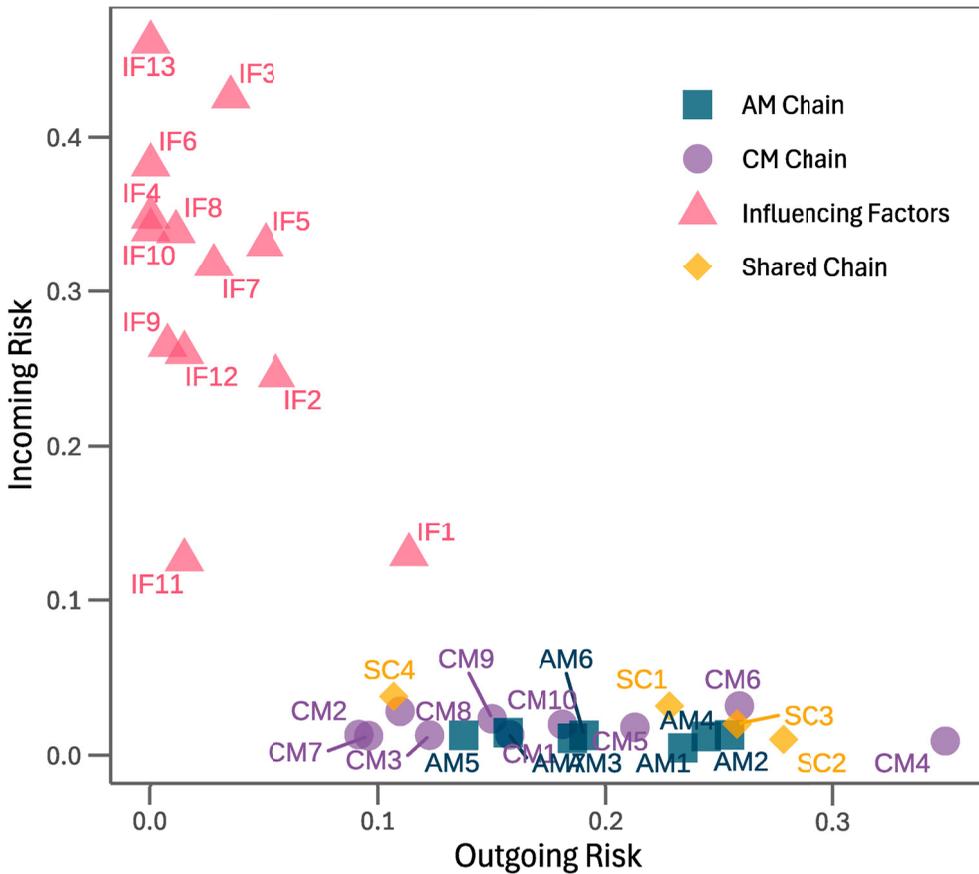


**Figure 6.** Resulting MDM for case 1 on application of the CPM algorithm for 3 steps. The height and width of the boxes in the intersection of elements show the combined likelihood and impact magnitudes for each combination.

challenges, which are driven by securing data sharing for intellectual property-sensitive designs with external service providers and managing potentially complex data administration (Kurfess and Cass 2014; Vogel 2016). This case study was primarily set up to examine these challenges.

**4.3.1. Case 2: study setup**

The simulation environment of the test-bed was set up with two OEMs acting as the customers, one material supplier, a dedicated company specialising in post-processing of printed parts, two research institutes taking up the role of AM service providers and a software company who had the role of providing the digital process support using their proprietary software. All companies and research institutes are based in Sweden. To put the use-case in context, Figure 8 shows a simplified process flow map of the setup.



**Figure 7.** Case 1: Aggregated risk values for each MDM element. The horizontal axis shows the outgoing risks and the vertical axis shows the incoming risks.

Table 3 presents possible associations between different disciplines & departments and the defined process steps. For instance, where external manufacturing occurs, a ‘handshake’ between the customer (OEM) and the supplier (AM Service provider (AM-SP)) takes place, which in turn depends on the type of agreement between the two parties. It can be  $A \rightarrow B$ ,  $B \rightarrow C$  or  $C \rightarrow D$ , depending on the capabilities of each organisation and the business model of the OEM. Further, there could be a procurement step with competing AM Service providers (Print houses). Here, separating who has access to which information becomes even more important. Finally, there could also be a varying degree of iteration loops, which further adds complexity to the physical and virtual flow.

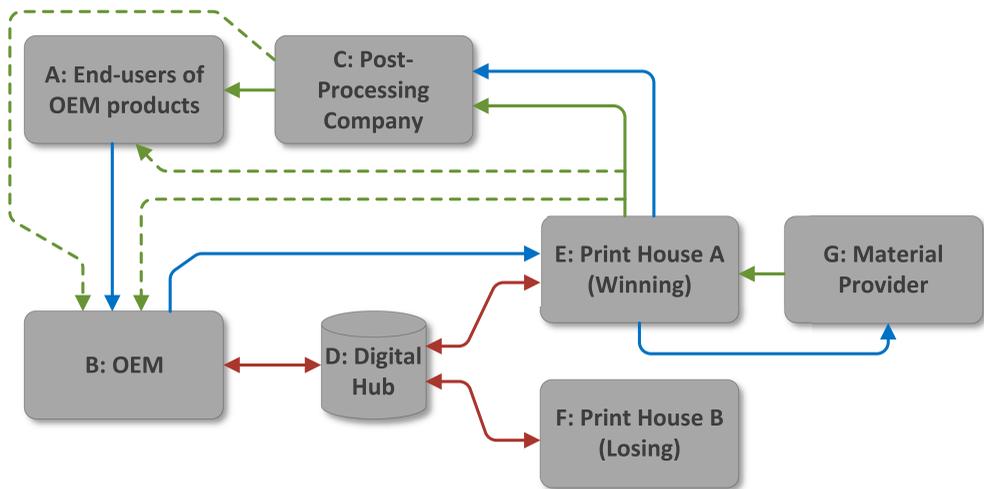
The aforementioned structure is first modelled as a process flow diagram, which is then converted to the MDM shown in Figure 9.

**4.3.2. Case 2: uncertainty elicitation**

Once the case was set up and the relationships defined, interviews were conducted to elicit the likelihood and impact values. The primary source of the data was the project coordinator, with inputs from representatives from each of the companies adding to the

**Table 2.** The list of influencing factors and the corresponding aggregated value of incoming risk for Case 1.

IF No.	Influencing factor description	Incoming Risk
IF1	V: Design requirements and constraints (R&C)	0.13
IF2	W: Design process chain	0.25
IF3	X: Digital process chain	0.43
IF4	Y: Product architecture	0.35
IF5	Z: Skill and expertise	0.33
IF6	AA: Intellectual property	0.38
IF7	AB: Supply chain	0.32
IF8	AC: Business strategy	0.34
IF9	AD: Organisational culture	0.26
IF10	AE: Organisational structure	0.34
IF11	AF: Testing compliance and verification	0.13
IF12	AG: Regulations	0.26
IF13	AH: Environmental Sustainability	0.46



**Figure 8.** Physical and virtual (data exchange) process map on organisation level. From the bidding phase to the product in operation. The blue arrows are orders, red arrows are data exchange, and green arrows are physical deliveries (dotted green arrows are alternative physical deliveries).

intra-organisation uncertainties. Figure 9 shows the overall MDM, including the influencing factor DSM and the relationships between the influencing factors and the case DSM. The values for these were also elicited by interviewing the coordinator of the project. Similar to Case 1, the matrix D is empty as the elements of the case flow affect the influencing factor and no reverse influence was expected.

Once the MDM was populated with the uncertainty values, the CPM algorithm was run on it for three steps, as described in the previous section.

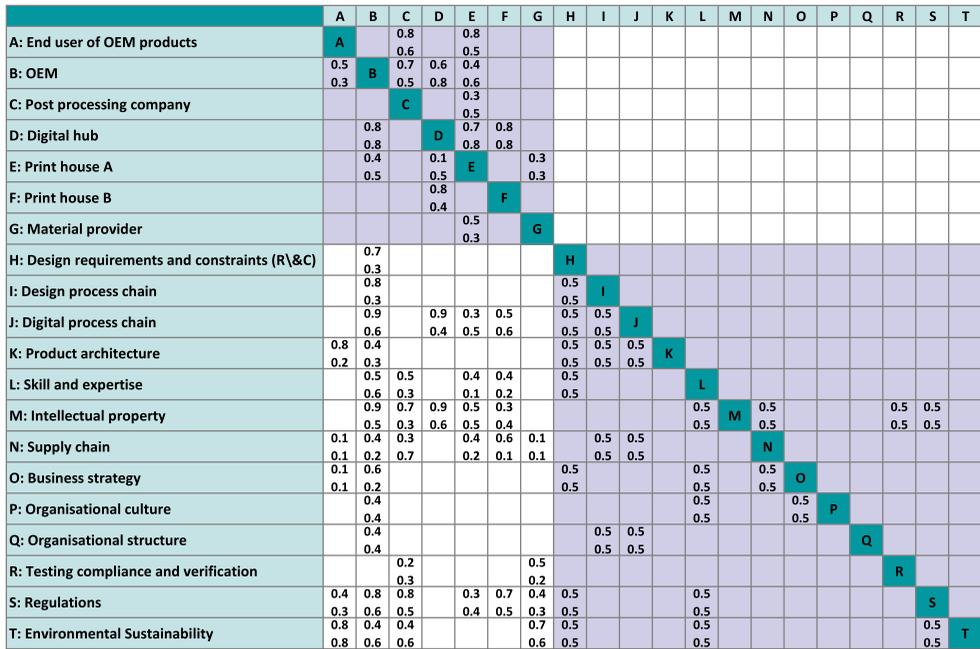
**4.3.3. Case 2: results**

Figure 10 (Right) shows the aggregated values of the combined risks for each of the MDM elements. For this case, IF6: Intellectual property was calculated to have the highest incoming risk and, therefore, the highest influence on the overall risk of the setup. Next was IF13: Environmental Sustainability, with a 27% risk, followed by IF12 and IF3, which are the

**Table 3.** Process flow associations for Case 2.

Organisation/Department/Discipline	<b>A</b> Product Design Functional Geometry	<b>B</b> Manufacturing Product Design, Layout	<b>C</b> Manufacturing Process Design	<b>D</b> Printing	<b>E</b> Post Manufacturing Processing
Ownership Dept	R&D/Product owner	R&D/Product owner	Production	Production	Production
Technical Discipline	CAD/CAE	CAD/CAM/CAE	CAM/CAE	Machine Operator	Machine Operator
Responsible Org	OEM	OEM or AM-SP	AM-SP	AM-SP	AM-SP
Sub Suppliers				Material Providers	HT, HIP, Machining

CAD = Computer Aided Design, CAM = Computer Aided Manufacturing, CAE = Computer Aided Engineering, OEM = Original Equipment Manufacturer, AM-SP = AM Service Provider, HT = Heat Treatment, HIP = Hot Isostatic Pressing



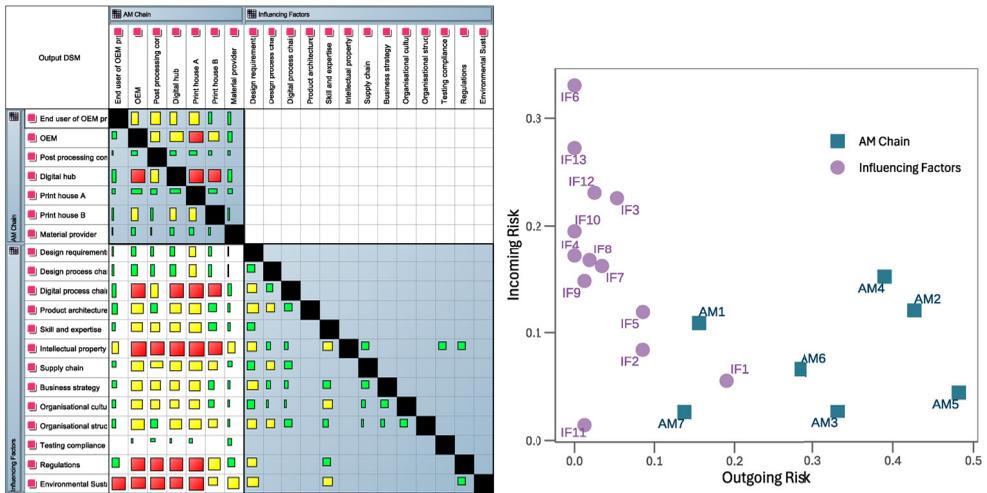
**Figure 9.** MDM of Case 2. The MDM is comprised of the case DSM, located at the top left corner of the MDM, showing the process flow of Case 2. The values on the top of each cell is the likelihood and on the bottom is the impact for each interaction.

**Table 4.** The list of influencing factors and the corresponding aggregated value of incoming risk for Case 2.

IF No.	Influencing factor description	Incoming risk
IF1	V: Design requirements and constraints (R&C)	0.06
IF2	W: Design process chain	0.08
IF3	X: Digital process chain	0.23
IF4	Y: Product architecture	0.17
IF5	Z: Skill and expertise	0.12
IF6	AA: Intellectual property	0.33
IF7	AB: Supply chain	0.16
IF8	AC: Business strategy	0.17
IF9	AD: Organisational culture	0.15
IF10	AE: Organisational structure	0.20
IF11	AF: Testing compliance and verification	0.01
IF12	AG: Regulations	0.23
IF13	AH: Environmental Sustainability	0.27

regulations and the digital process chain, respectively. The incoming risks for Case 2 are summarised in Table 4.

For this case, it was also particularly important to analyse the outgoing risk factors carefully. Unlike Case 1, multiple organisations are involved in this test-bed, where different organisations may have different contributions to the overall risk values. AM5: Digital hub, has the highest propensity to propagate risks to other components of the system, even though its own risk exposure is very low. Similar are the cases for AM4: Post processing company and AM2: The end user of the product. Such elements which have low incoming



**Figure 10.** Case 2: (Left) Resulting MDM for Case 2 on application of the CPM algorithm for 3 steps. The height and width of the boxes in the intersection of elements show the combined likelihood and impact magnitudes for each combination. (Right) Aggregated risk values for each MDM element. The horizontal axis shows the outgoing risks, and the vertical axis shows the incoming risks.

risk but high outgoing risk are called risk multipliers (Clarkson, Simons, and Eckert 2004), which propagate more risk than they absorb.

### 5. Discussion

The two cases show how different initial conditions, in form of dependencies and workflows, can manifest as different risk outcomes for various cases. The method discussed in this paper enables such an analysis for an organisation which wants to implement AM in its existing workflow and assess the risks. Although it is not presented in this paper, the paper also allows for multiple scenarios to be tested for every single case. This can allow for an even more in-depth analysis of the risks. Further, analysis of the results also reveals some generalised insights, which are discussed as follows. These insights have potential implications for the overall challenges of the industrialisation of AM. A few of these insights also highlight some of the limitations of the approach presented.

*Complexity of workflow.* Workflows and information flows in an established company are usually highly complex, which makes it very difficult to capture them in a formal way. Figure 4 for instance, shows the workflow for the part shown in Figure 3. Such processes are highly reliant on the experience of design engineers and are often iterative, which makes capturing the process accurately quite difficult. It is also often not possible to capture the process to a high level of granularity, thereby losing information in the process. The resulting workflow description, therefore, is always somewhat simplified. Further, the tacit information that engineers almost always rely on is also expected to be somewhat lost. Another aspect is the geographic concentration of the cases used to arrive at these insights. The insights presented in this paper are based on case studies from Swedish manufacturing companies, which may limit their applicability in other industrial contexts, geographic regions, or sectors with different manufacturing practices and cultures.

*Holistic assessment.* The methodology presented in the paper offers a more comprehensive alternative to traditional methods, such as DfAM, by addressing the broader integration challenges of AM into established workflows. While DfAM focuses primarily on optimising part designs for, the approach presented in this paper emphasises the proactive identification and mitigation of risks within the entire manufacturing value chain and provides actionable insights into hidden dependencies and uncertainties that could hinder implementation of AM.

*Scope of risk factors.* While the methodology addresses 13 factors which influence risk associated with the adoption of AM, they are mostly based on literature survey with very minimal input from the cases. Therefore, the list may not encompass all potential risks, such as those arising from rapid technological changes or unforeseen market dynamics.

*Quality of data.* Some companies utilise product lifecycle management (PLM) tools to support the process of workflow management, capture of design rationale and other data for record keeping. This can be a highly valuable source for eliciting dependencies for the MDM. However, the likelihood and impact values which drive the risk analysis will still need expert opinion, which can be subjective. This is a significant limitation of quantitative risk analysis methods in general. However, the literature points to several ways to address this. For example, the method presented in this paper could be adapted for Monte Carlo simulations where probability distributions are used instead of a single likelihood-impact pair. There are several examples of such adaptations of CPM (see Brahma and Wynn (2022) for a review on the topic). Further, data for likelihood and impact can also be drawn from historical data. However, this is not always available for smaller organisations or may be available in formats which need translation into uncertainty values appropriate for this method. Further, the paper does not dive deep into the long-term challenges related to workforce training and skill development necessary for implementing AM technologies. Factors such as skill are also often difficult to quantify.

*Reliance on digital systems.* The analysis also showed how the industrialisation of AM was highly reliant on digitalisation and digital systems. For both cases, the risk values for the digital process chain and related factors of intellectual property were significantly high. The second case, for instance, showed how software can be used to manage all the data access-related challenges in the process, which can help in the protection of IP and ensure what information is available to whom and to what extent. However, this is also very subjective to the process and the organisational setup and, therefore, difficult to capture sufficiently with approaches such as DSMs or MDMs. For example, such setups may be dependent on how non-disclosure agreements are set up between organisations in the workflow. Capturing the fine print of such setups can be challenging in the method described in this paper.

Further, there is also the issue of cross-functional IT systems. Companies that participate in such workflows may have different IT infrastructures, leading to a lack of interoperability. Such uncertainties are not always visible at the early stages of AM implementation and, therefore, must be captured properly in the uncertainty values in the method described in this paper.

*Decision support tools.* The method presented in this paper is a form of decision support for companies who want to implement AM in their workflows. However, there is also a lack of decision-support tools post-implementation of AM. Once implemented, designers have to choose for each design whether they want to use AM or use other traditional methods of manufacturing for a part. Such decision-making is particularly difficult when there are

multiple criteria such as sustainability, reliability, maintainability, flexibility and so on, and are beyond the set criteria of cost, lead time and performance.

One of the related challenges for the method is the variability of the workflow between parts. While in traditional design processes, tasks such as details surrounding assembly and manufacturing may only be considered after the design process, in AM, the consideration of manufacturing, assembly, and functionality/performance are correlated and not independent. This highlights the potential conflicts a company may have if they have both conventional and AM processes in its manufacturing portfolio. The source of this complexity is primarily from the design freedom AM has to offer. Some of these risks, such as those related to product integrity, reliability and other complexities of post-processing, may be solved using simulation tools within the workflow, which, however, can be expensive and make the workflow significantly more complex. Related to such risk are also aspects of certification and testing. Digital capabilities of simulation and testing may help mitigate such risks as well.

*Risk values and process repeatability.* AM also has its challenges related to material sourcing and availability (e.g. varying material quality), which can lead to risks of process repeatability. This can have a significant effect on the quality control of parts produced. Such variability is, however, difficult to capture in the method described in this paper. Previously mentioned methods such as Monte-Carlo simulations to simulate such variability can help in gauging the risks properly. Additionally, companies should ensure the availability of digital infrastructure to capture the traceability of data for materials, which may also help in mitigating some of the risks related to certification and testing.

## 6. Conclusion

There has been a rapid development of AM in the last few decades, leading to new manufacturing and business opportunities. As a result, many companies are looking to integrate them into their existing value chains. However, being radically different to the traditional methods of manufacturing, it brings significant challenges. Companies are unable to foresee the resulting risks, which lead to either complete failure of implementation or extremely high rectification costs. In this paper, we presented a method of assessing risks based on the current and the anticipated workflow of an organisation after the implementation of AM. The method is applied to two cases from a long-running project in Swedish OEMs. First, observations are made from the two cases leading to the elicitation of the workflows. The workflows are mapped into MDMs, along with 13 influencing factors derived from the literature. The dependencies in the MDM are then populated with uncertainty values in terms of likelihood and impact. A risk analysis algorithm is then used to assess the risk propagation and the final risk values for the system. The overall risks are evaluated on the 13 risk factors.

Analysis of the results shows that this type of approach can give a quantitative view of issues that may not be obvious but may have significant ramifications when it comes to the success of AM implementation. An objective and quantitative evaluation of the risks in a company before implementing AM can increase the chance of success. Further, the method can be used as a decision-support tool which can help managers evaluate digitalisation-related risks surrounding AM and in companies with existing manufacturing ecosystems. The paper presents applications of the method in two industrial cases.

However, the study has some limitations. The complexity of workflows makes accurate representation challenging, leading to possible loss of contextual information. The risk factors, mostly derived from literature, may not fully cover case-specific risks, and reliance on expert opinion introduces subjectivity. Additionally, the geographic focus on Swedish manufacturing companies may limit the insights' generalisability.

In the future, we intend to address these limitations by including more diverse case studies and integrating simulation techniques, like Monte-Carlo, to better account for variability. Developing computer-based decision-support tools and enhancing digital infrastructure for data traceability would also improve the method's applicability. By addressing these limitations and advancing the methodology, the proposed risk assessment approach can become more comprehensive and widely applicable, ultimately supporting more successful adoptions of AM in diverse industrial contexts.

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