Implementation of Rapid Manufacturing for Mass Customisation

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Abstract

Purpose
The paper aims to increase the understanding of how companies can implement Rapid Manufacturing (RM) (i.e. the use of Additive Manufacturing (AM) technologies for final part production) for mass customisation (MC), drawing upon the experiences of firms in the dental sector (one of the major users of AM technologies).

Design/methodology/approach
A framework for implementation of RM for MC was developed from the literature to guide the data gathering. Data from six case companies in the dental sector implementing RM for MC, supplemented with insights from their respective AM machine providers and software companies, were used to analyse how companies implement RM for MC and what considerations and challenges they face in the process.

Findings
The study shows how implementation of RM for MC entails different considerations depending on stage of implementation and maturity of involved technologies. 26 challenges have been identified that seem to play a crucial role in implementation. The paper suggests that RM can enable MC in manufacturing by achieving both a high number of units produced and as well as a high level of customisation of each product.

Originality/value
Based on our review of the literature, no case studies exist that investigate companies implementing RM for MC despite literature having suggested RM as an enabler for MC in manufacturing for many years.

Keywords
Additive Manufacturing (AM), Rapid Manufacturing (RM), Mass Customisation (MC), Advanced Manufacturing Technology Implementation

Paper Type
Case study

1 Introduction

Additive manufacturing (AM), a process of creating an object through the additive application of joining materials from a 3D data file, has the potential to enable the production principle of mass customisation (MC) (Fogliatto et al., 2012). The direct production of objects with AM is called 'rapid manufacturing' (RM), and offers advantages compared to traditional manufacturing methods. These advantages include customisation and flexibility which are said to come "for free" (Weller et al., 2015, p. 46). Despite these advantages, there has been a lack of studies investigating the implementation and use of RM for MC purposes in specific industries (Fogliatto et al., 2012; Mellor et al., 2014; Sandström, 2015).

Ruffo et al. (2007) describe three areas of challenges that enterprises have to face when looking to utilise RM as a manufacturing process:

1. Manufacturing processes and materials
2. Design
3. Management, organisation and implementation

This paper addresses the third point, with a focus on implementation, and seeks to increase understanding of how companies implement RM for MC.

Of the industries suggested by the literature and industry experts (Wohlers, 2015) which implement RM, only a select few fulfil the requirements for mass customisation applications. These require the production of individualised products at near mass production volumes (Piller, 2008). There are a number of appropriate RM applications for MC in the medical field (Mellor et al., 2014) and research by Atzeni and Salmi (2012) and Deradjat and Minshall (2015) has identified the dental industry to be a potential area of investigation. Our study focuses on the dental sector for the following two reasons. Firstly, the dental sector provides an appropriate number of companies that are implementing and have implemented RM for MC for our analysis. Secondly, no research has been conducted focusing on the implementation of RM for MC in the dental sector.

Our research aims to address gaps in literature on MC through RM by providing an understanding of how enterprises implement RM for MC in the dental industry. Additionally, for practitioners in industry, the paper seeks to identify challenges that are involved with introducing and operating an RM production system for MC to better inform firms regarding potential issues that may have to be addressed. Thus, this paper seeks to answer the following questions:

Research question: How do companies implement RM for MC in the dental industry?

Sub-question: What considerations (i.e. aspects that companies have to take into account) and challenges (aspects that can present obstacles) do companies have to address when implementing RM for MC in the dental industry?

As ‘considerations’ can also represent challenges and vice versa, the paper will not label them separately but will instead present them as ‘considerations and challenges’ in a combined form.

In the following section, we review the literature on MC and RM. The subsequent section presents the design of the research framework drawn from the literature for structuring data gathering to help address the research questions. Next, the research methodology and contextual information regarding the case companies are presented. Insights from the six case studies structured around the categories of the research framework are then used to address the research questions. The paper finishes with the conclusions, limitations of the research and suggestions for further research.

2 Literature review

2.1 Additive Manufacturing technologies and Rapid Manufacturing

Rapid Manufacturing is a term used to describe the use of Additive Manufacturing for final part production. Hopkinson et al. (2006, p.1) define Rapid Manufacturing (RM) as

"the use of a computer aided design (CAD)-based automated additive manufacturing process to construct parts that are used directly as finished products or components".

The term additive manufacturing (AM) refers to "the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" (ASTM, 2012, p. 2). AM can be classified according to the method of material supply into liquid based, solid based and powder based systems (Wong and Hernandez, 2012) Figure 1 shows a selection of the most industrially relevant AM-processes. The case studies within this research deal with the processes of Selective Laser Sintering (SLS), Selective Laser Melting (SLM) and Direct Metal Laser Sintering (DMLS). In these processes metal powder is applied to the build platform with powder coater and melted by a high-power laser (Gibson et al., 2010). The pieces are attached to the build platform and for the applications considered in this study require support structures which position the pieces (Gibson et al., 2010). These support structures have to be removed and the work pieces need to be post-processed through for instance milling and may require heat treatment to remove internal stresses created during the AM process (Mumtaz and Hopkinson, 2010).

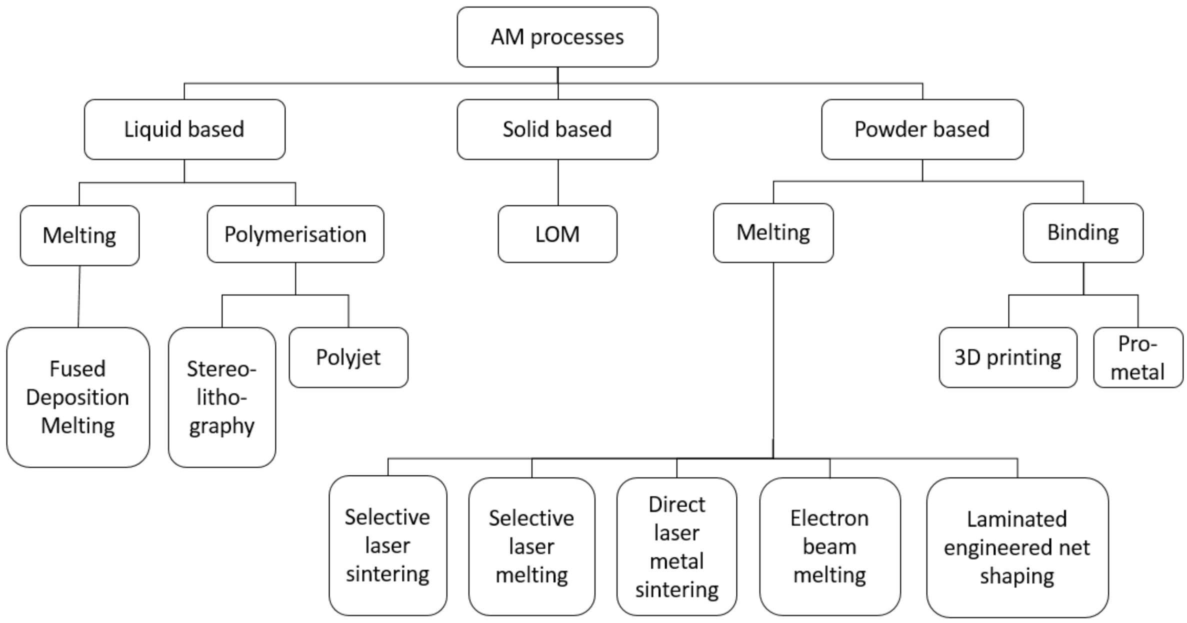

Figure 1: Classification of additive manufacturing technologies based on Wong and Hernandez (2012)

RM developed from the term rapid prototyping (RP) which was used first in the 1990s to describe the quick creation of prototypes (Atzeni et al., 2010). The manufacture of prototypes could be realised either by addition or subtraction of material (Pham and Dimov, 2001). The technology utilised in RP was later employed for the production of tools which was termed rapid tooling (Pham and Dimov, 2003). Rapid tooling generally applies to the creation of moulds and tooling inserts using RP technology (Pham and Dimov, 2003). The relatively poor mechanical properties of the early AM produced objects (Kruth et al., 2007) have been improved as the result of increased R&D in AM within the last 5-10 years allowing for the emergence of RM (Mellor et al., 2014).

Holmström et al. (2010) attribute the following benefits to AM technology employed for RM:

1. Absence of tooling requirements reduces production time and expenses
2. Small production batches become feasible and economical
3. Quick design changes are possible
4. Production can be optimised in regard to functional purposes
5. Custom products become economically viable
6. Waste is reduced
7. Supply chains can be simplified
8. Design of products can be customised

The inherent benefits of AM as discussed by Holmström et al. (2010) in theory allow the realisation of production strategies such as MC as it allows customisability of products (Fogliatto et al., 2012). Reeves et al. (2011) and Gibson et al. (2010) discuss the potential of RM for MC approaches. The literature on RM and MC, however, either only describes future applications and implications for MC and RM or mentions existing examples in the medical industry (specifically hearing aids, dental products and surgical applications) and consumer goods industry in a relatively superficial way without investigating the industrial and technical context further (Gibson et al., 2010).

Sandström (2015) describes the adoption of AM by the hearing aid industry from 1989-2008. The study shows that AM did not have a disruptive effect on the industry.

After a review of literature, Mellor (2014) finds that the following barriers exist in the context of RM implementation:

- High capital investment
- High material and maintenance costs
- Insufficient material properties
- Difficulties with material removal
- High process costs

Much of the literature on RM, and consequently on RM for MC, appears to be based on hypothetical and/or potentially outdated cases. As such, there is a need to reinvestigate the earlier identified challenges and explore the current state of RM implementation, especially in the light of fast technological progress within recent years (Khajavi et al., 2014).

2.2 Mass Customisation

The term “mass customisation” was originally coined by Davis (1987) to describe the contradictory production strategy of realising mass production of customised objects; the principle was later developed by Pine (1993) (Duray, 2011). The underlying theory in literature for mass customisation is based on Hayes and Wheelwright's (1979) product process matrix (Duray, 2011). Within the product variety matrix adopted in literature (Krajewski et al., 2007; Schroeder, 2007; Stevenson, 2009), MC attempts to bridge classic mass production and one-of-a-kind production. Figure 2 depicts the positioning of mass customisation approaches within the discussed matrix between mass production in the lower right-hand corner and production of different individual products in the top left-hand corner (Tuck et al., 2008).

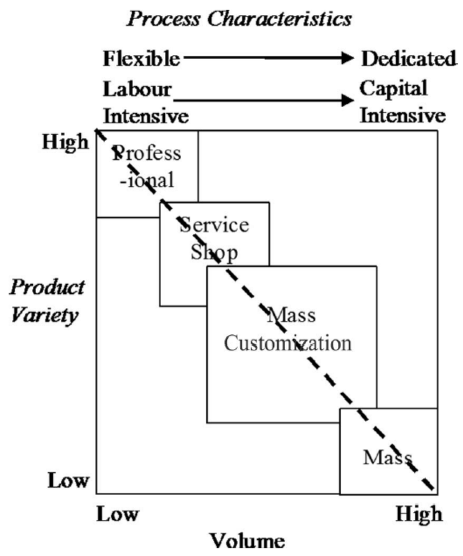

Figure 2: Product variety-volume matrix (Tuck et al., 2008)

The term "customisation" implies that the customer has to be involved in the design process at some point in the product creation process (Lampel and Mintzberg, 1996). Lampel and Mintzberg (1996) classifies customisation into the three categories of pure, tailored and standardised with each stage differing from the other in terms of its uniqueness and the degree to which a customer is involved. The earlier the customer is involved in the production process, the higher the degree of customisation.

There is no real consensus in the literature on the definition of the level of customisation and production volume required that qualifies the term MC (Bateman and Cheng, 2006). On one side there are advocates of MC that believe that MC only exists if the customer can fully customise the object in every regard, on the other side more pragmatic scholars consider the product creation and delivery according to some customer requirements to constitute MC (Silveira et al., 2001). Hart (1996) believes that the compromise for these divergent views is to identify the realistic and appropriate range of customisability of a product and how customers make demands on this range. Westbrook and Williamson (1993) think that MC can only be successfully implemented if customisability is combined with standardised processes that offer high part variety.
Similarly, the literature does not specifically define the level of production units required related to MC. Instead, Duray et al. (2000) and Pine (1993) suggest that production costs of MC should ideally be close to mass production levels.

To make MC economically viable, Pine (1993) suggests the degree of customisation be limited to the customer. Specifically, the principle of modularity in the product creation process is to combine standardised and customisable components. Modularity realises the feasibility of producing objects on a "mass" scale while variable elements ensure the customisation aspect. Many scholars believe that MC for the creation of physical products has to be restricted and combined with modularity in order to successfully work (Duray, 2011; Piller et al., 2004; Piller, 2008; Pine, 1993). Silveira et al. (2001) claim that one of the core activities for a successful implementation of MC is the concentration on value and the elimination of waste in all production steps and the reorganisation of value-creating activities into efficient processes at high variant and production levels.

The literature on MC has significantly increased from 2001 with the emergence of web-based software tools, the development of systematic customer-interaction models and the emergence of RM technologies (Fogliatto et al., 2012). Fogliatto et al. (2012) have reviewed literature on MC and classified it into four different literature areas: (i) the economics of the principle (ii), success factors, (iii) MC enablers and (iv) customer-manufacturer interaction.

With the aforementioned benefits of AM technology and RM, particularly in regard to the degree of customisation, this study aims to target the literature on MC enablers which can be further classified into four categories describing methodologies, processes, manufacturing technologies and information technologies (Fogliatto et al., 2012; Silveira et al., 2001), as shown in Figure 3.

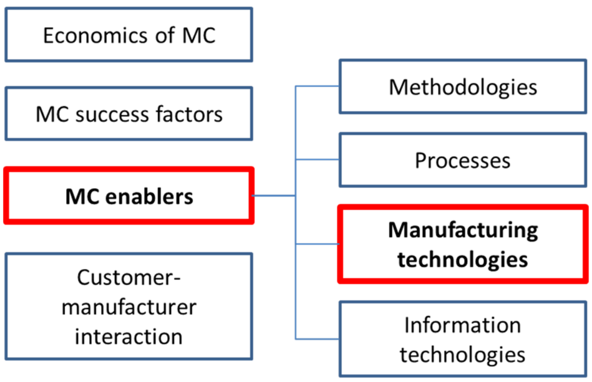

Figure 3: Classification of MC literature

Literature on MC enabling manufacturing technologies has so far primarily focused on computer-aided design and 3D laser scanner in the clothing, garment and shoes industries (Fogliatto et al., 2012). A literature search conducted by Fogliatto et al. (2012) reveals the lack of research on implementation models of manufacturing technologies for MC and the lack of cases that illustrate successful implementation of MC in manufacturing. Despite recent research attention of RM technologies for MC, the literature appears to be still scarce. Similarly, barely any studies seem to have targeted the business management implications of RM and MC (Fogliatto et al., 2012).

In this paper MC is understood as a production strategy which implies the production of individualised and unique products in production volumes that are comparable with mass production. It is important to note that each product is different from another in shape and that a full degree of mass customisation cannot be attained through principles such as modularisation which offer a selection of different variants.

Investigating the challenges involved that prevent the successful application of RM for MC will both help explain the current lack of academic research and limited examples in industry as well as provide a theoretical base for future research in this area. It is thus important in the light of insufficient research in this area to understand relevant factors associated with an implementation of AM technology. Mellor et al. (2014) propose a framework for AM implementation by considering strategic, supply chain, operational, organisational and AM related technological factors and how these are influenced by external forces (Figure 4). The framework, despite providing valuable insights, has two shortcomings: Firstly, it is very generalised and does not account for technical factors such as necessary software components and post-processing variables. Deradjat and Minshall (2015) stress the importance of these elements for production with AM.

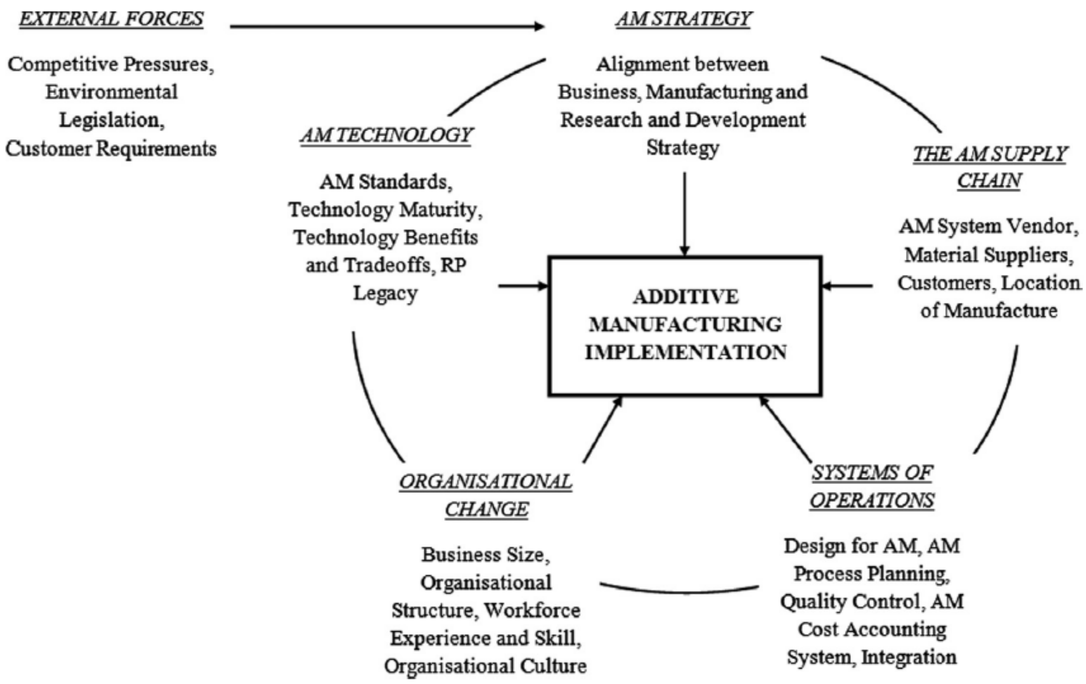

Figure 4: Framework for AM implementation (Mellor, 2014)

Secondly, the proposed variables can be different depending on the point in time during the implementation process as suggested by Voss (1988). Mellor et al. (2014) do not recognise this differentiation in the proposed framework. Voss (1988) constructs his definition of technology implementation along a life-cycle model in terms of a three-stage sequence (Figure 5). The first phase, labelled “pre-installation” represents all the variables that are relevant to the success or failure of the entire endeavour. This stage comprises an evaluation for further action into the next steps. The second step, installation and commissioning, ideally ensures the successful realisation of a working order of the applied technology on a consistent level. In the final post-commissioning phase, further technical and business activity improvement occurs. Voss (1988) states that it can be argued that the last phase should never end, as an effective enterprise should continue to strive for improvement.

Figure 5: Life-cycle model of the implementation process (Voss, 1988)

Our review has revealed that with the benefits and advances of AM technology, RM has the potential to become an enabler for MC. While there is research on RM and MC, there is a gap where these two fields of research intersect. Despite evidence from the literature and regulatory bodies underlining the necessity to investigate how AM facilitates MC, there are no appropriate studies on the topic. In order to address the lack of literature for MC through RM, it would be beneficial as a first step to assess the factors and challenges involved in combining and implementing these two principles. An implementation framework of RM for MC needs to be developed from existing implementation frameworks for AM in order to provide a structure for data gathering to allow us to address the research questions.

3 The research framework

This section draws upon concepts from the literature to derive a framework for RM implementation for MC to structure the data gathering.

Deradjat and Minshall (2015) propose a framework of AM implementation for MC in which technological, operational, organisational and internal and external factors are considered. The model emphasises the importance of technical considerations that have to be taken into account: In this context, technological factors are clustered according to the process flow of an AM process: Front-end factors capture software and data manipulation aspects. Equipment related aspects such as raw material, maintenance and product quality and speed relate to the specific AM machine used. Back-end considerations comprise part removal from the AM platform, mechanical post-processing and heat treatment. Overall process challenges capture variables that encompass the entire production such as technology maturity, process consistency, etc. While the framework stresses the importance of technological factors, just like Mellor et al. (2014), it fails to accommodate the stage of implementation process. Additionally, it does not account for interdependencies between the listed factors but rather portrays these as independent variables. The three implementation phases are pre-installation, installation and commissioning (abbreviated as installation phase for the rest of the paper) and post-commissioning phase.

Since these existing frameworks have significant shortcomings, we propose a framework for RM implementation of MC that provides categories of factors to help understand potential challenges involved relating to the lack of research on MC enablers in manufacturing. Figure 6 captures the factors relevant for AM implementation.

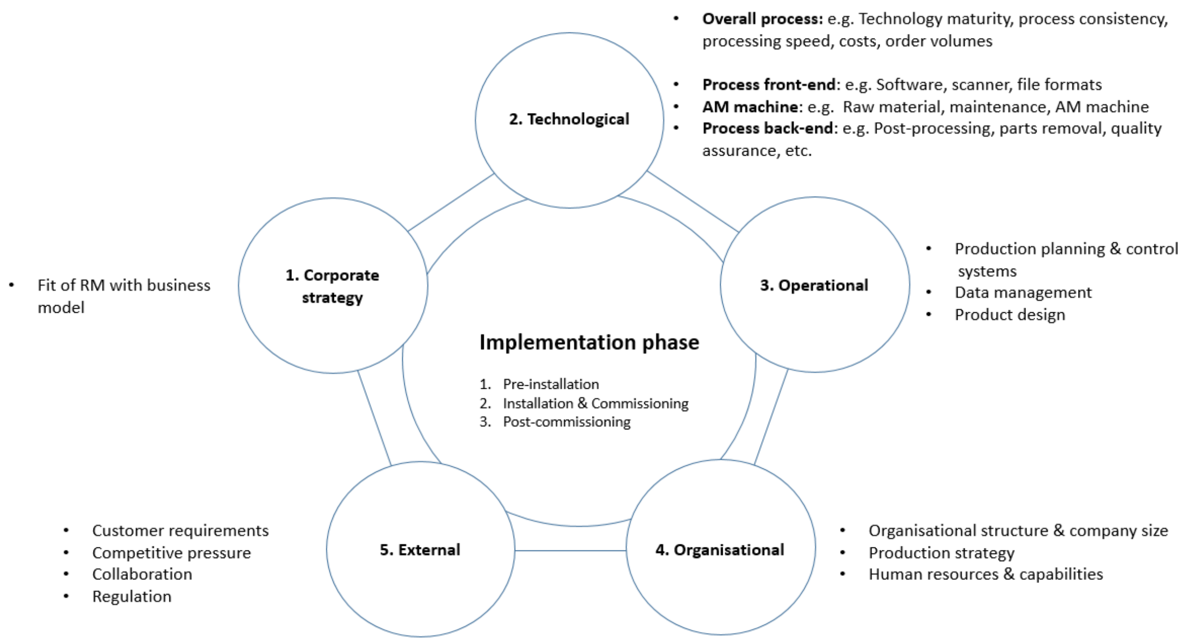

Figure 6: Framework of Rapid Manufacturing implementation for Mass Customisation

Each category of the framework can be described as follows: Corporate business strategy has a direct influence on technology implementation (Saberi et al., 2010). A particular focus is set on the technological aspects as AM presents a technology which is different from traditional manufacturing processes (Gibson et al., 2010). The framework incorporates front-end, AM machine related, and back-end factors similar to Deradjat and Minshall (2015) and factors such as production speed, costs, order volumes and technology maturity. The later in particular has been shown by Frohlich (1998) to be relevant for companies adopting manufacturing technology at an early technology maturity stage.

Operational variables such as production planning, control systems and product design are areas which can be of relevance for implementation of AM for MC as Silveira et al. (2001) state the importance of efficient allocation of resources. Studies on production planning for AM are lacking according to Mellor (2014). Work with limited applicability to RM on the relevance of process planning for AM has been carried out by Munguía et al. (2008) with RP enterprises.

Organisational factors such as the size of an enterprise have been recognised as playing a role in the outcome of novel technology implementation. Federici (2009) and Welsh and White (1981) state that the size of a company matters when applying theories to enterprises; theories valid for large companies may not necessarily be valid for smaller ones. In particular research has shown that the organisational structure of a company can be crucial for implementation of an advanced manufacturing system like AM (Dean et al., 1992; Saberi et al., 2010). Additionally, production strategies and human resource related challenges have to be taken into account according to Saberi et al. (2010) and Voss (1988).

External factors capture, similar to the ones proposed by Saberi et al. (2010), comprise customer requirements/interaction, competition, collaboration with external partners and the regulatory environment.

The centrepiece of the framework is the differentiation of the other five categories according to implementation phases suggested by Voss (1988): Pre-installation, installation & commissioning and post-commissioning. As Voss (1988) highlighted, challenges and actors involved during an implementation phase vary and thus will have an influence on the above mentioned five aspects. The suggested framework will be used to support analysis of RM implementation for MC in six case companies.

4 Research methodology

Considering the novelty and exploratory nature of the suggested research area, a case study approach has been chosen. The research employs a multi-case design in order to allow comparisons between different cases as well as strengthening the robustness and generalisability of the findings (Herriott and Firestone, 1983). As this paper aims to analyse more than one aspect in order to assess the complexity of implementing RM for MC, multiple units of analysis are needed. Thus, an embedded multi-case study design according to Yin (2009) will be most appropriate for this study. Six companies having implemented RM for MC in the dental industry have been analysed. The proposed implementation framework serves the purpose of providing a structure to the data gathering, i.e. the interviews. In particular, the framework categories corporate strategy, technical (overall RM process, process front-end, AM machine, process back-end), operational, organisational and external considerations will help facilitate the data gathering.

The interview questionnaires were linked to the main categories of our framework (Figure 6) to allow us to break down the overall research question of how companies implement RM for MC. In regard to each framework category questions were asked. Academic literature and publicly available information on the case companies were used to customise each questionnaire. The main questions are listed in Table 1.

Table 1: Summary of interview questions

1. Corporate strategy When did the company implement RM? How long did it take? How did RM fit into the corporate strategy?	
What were the X considerations and how did the company implement them for RM of MC? What were the X challenges? Did the considerations and challenges change throughout the implementation process/time? If so, please describe how they changed/what other considerations and challenges emerged?	
	2. Technical
X=	Overall process (e.g. technology maturity, process consistency, processing speed, costs, order volume)
X=	Process front-end (e.g. software (customer and company side), scanners/geometry capturing, file formats)
X=	AM machine related (e.g. raw material and maintenance, AM machine)
X=	Process back-end (e.g. post-processing, parts removal, quality assurance)
X=	**3. Operational** (e.g. production planning and control systems, data management, product design)
X=	**4. Organisational** (e.g. organisational structure and company size, production strategy, human resources and capabilities)
X=	**5. External** (e.g. customer requirements, competition, collaboration opportunities/need for collaboration, quality standards, etc.)

For each company, interviews were conducted with representatives who are familiar with RM implementation. Publicly available financial data from annual reports and governmental data bases have been used to supplement the case studies. In order to increase validity of the cases, data derived from interviews and email exchange with engineers of AM machine producers and the software company supporting AM production have been added. Relevant insights from the interviews for RM implementation for MC as well as information contradicting these are presented in the next section. Information obtained in the interviews that are not relevant to the research topic are not considered.

To account for differences of implementation factors due to firm size as postulated by Schroder and Sohal (1999) and Welsh and White (1981), both large firms as well as small and medium sized (SME) companies have been investigated. The classification is based on European Commission (2003). Table 2 captures details on our six case companies underlining their suitability as case studies for MC in regard to production output. Relevant AM machines and informants are listed in Table 3. Further contextual explanation of the companies and their relation to RM will be provided in section 5.1. Table 3 provides a summary of one key technical parameter (i.e. build platform size) for AM machines. Comparing the build rate of the machine is not feasible as it is dependent on variables such as material, density and geometry. Build platform dimensions may have been marginally altered to anonymise the machine model.

Table 2: Information on case companies

	AM Products	**Number of units produced per year**	**AM machine model and number of machines (See table 2 for abbreviations)**	**Size of company**	**Other**	**Informant**
Company A	Copings, frameworks	not specified	A1, B1, B3 Overall 13	US based company, > € 50 m annual sales	Produced dental products with CAM before, production facility abroad	Informant A: Implementation engineer and business developer
Company B	Implant bridges	not specified	C1 Overall 1	US based multinational company, > €3 b annual sales	Produced dental products with CAM before, production facility abroad	Informant B: Process engineer responsible for AM implementation
Company C	Crowns, implant bridges	> 600,000	A1, A2 Overall number not specified	German SME, € 70 m annual sales	Produced dental products with CAM before, production facilities abroad	Informant C: R&D & Production egnineer
Company D	Crowns, bridges, Implant Prothestics	> 100,000	A1 Overall 6	Germany based, € 350 m annual sales	Produced dental products with CAM before	Informant D1: Global head of R&D Informant D2: Lead production manager
Company E	Crowns, bridges, smaller implants	> 50,000	A1 Overall 2	German SME*, 18 employees	E distributed dental products but never produced before	Informant E: Head of Production
Company F	Crowns (40%), medical implants (40%), Other	> 15,000	B1, B2, B3 Overall 3	German SME*, < 30 employees	Dental lab group founded F for AM production	Informant F: CEO and head of production

* SME classification according to EU recommendation 2003/361: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32003H0361

Table 3: Description of AM machines used in the study

AM machine Manufacturer	AM machine		Build platform	Informant
A	A1		250 mm x 250 mm x 215 mm	Informant AM1: Application engineer for dental applications Informant AM2: Technology consultant
	A2	Upgraded A1 version	250 mm x 250 mm x 300 mm	
	A3		Ø 100 mm x 95 mm	
B	B1		250 mm x 250 mm x 250 mm	Informant BM: Production engineer, dental applications
	B2	Different number and type of lasers to B2	250 mm x 250 mm x 250 mm	
	B3		90 mm x 90 mm x 80 mm	
C	C1		250 mm x 250 mm x 300 mm	Informant CM1: Senior Development Engineer of dental division Informant CM2: Business development manager dental products

5 Results and discussion

The data presented in this section serves to answer the research questions by providing a description of how companies implement RM for MC and by identifying the challenges and considerations they face. The results are presented according to our framework (Figure 6). The technical framework considerations in particular, unlike the others, will be subdivided into four subsections for the discussion of the results as the developed framework places an emphasis on technical aspects. While these four subsections and the framework categories (denoted in bold font in Figure 6) provide a structure to the presentation of results, the other factors in the framework merely serve as suggestions of potential considerations and challenges. Each of the five framework factors will be divided according to the implementation phases suggested by Voss (1988) if there are distinctly different considerations within each of the steps. To reduce the complexity of presentation, results for pre-installation and installation phase have been merged as many considerations overlapped. If companies were not named for certain challenges, this means that the respondant did not identify the topic as a relevant consideration to the implementation process.

5.1 Corporate strategy and context

This section provides information about the context of RM implementation in regard to the corporate strategy of the case companies. The insights provide important contextual understanding for the data discussed in sections 5.2-5.5., and explains the underpinning motivation for the case companies implementing RM for MC.

The dental sector offers a wide range of metal dental products such as dental crowns and frameworks that traditionally are manufactured through processes such as casting or milling. Dentists usually order such products from large milling centres or smaller dental labs. With a large number of manufacturers, the dental market for such metal products is fragmented. With maturing AM technology, a small number of companies have started adopting RM in place of these traditional production systems.

The larger case companies were undergoing changes to adapt to digital technologies in dentistry prior to investing in AM. Company A decided to make the necessary changes to accommodate the rising importance of digital dentistry in 2006. The company has adapted operations to fully integrate CAD-CAM technologies. Company B had a CAM-milling process for dental frameworks in place before adapting RM and is transitioning into RM in order to be able to scale up production more cost efficiently.

Company B had been investigating AM as a potential manufacturing process for several years. The challenge that Company B had difficulty addressing was the transfer of the products for the necessary milling post-processing step. Company B and AM Machine Manufacturer C decided to enter into an agreement in which Company B purchases Manufacturer C's AM process for the production of dental products and AM Manufacturer C terminates its distribution and development of its implant-supported frameworks. Company B has started the implementation process in February 2015 and is looking to launch clinical production towards January 2016. The decision to acquire a fully working process reduced the implementation process from two to three years as for other companies to just under a year.

Company C is the first company to have applied RM for dental applications and filed patents in this area. The company continues to invest significant sums into its digital dentistry operations for structural development.

Company D initiated investment into digital dentistry well before 2007 when the company developed intra-oral scanners and launched an integrated CAD/CAM-system for dental laboratories. Investment into R&D was largely allocated to develop and implement the system and to transition the company's manufacturing capabilities towards digital.

Companies E and F were founded by individuals owning a network of dental laboratories to both supply internal demand and produce for other companies. These companies had to closely collaborate with AM machine producers and execute the pre-installation and installation phase with governmentally funded project and academic research institutes.

5.2 Technological factors

In order to present technological factors in a more structured manner, aspects are separated according to the overall process, front-end, the AM-process and back-end.

5.2.1 Overall process related factors

Figure 7 illustrates the process chain for the dental products investigated in this paper.

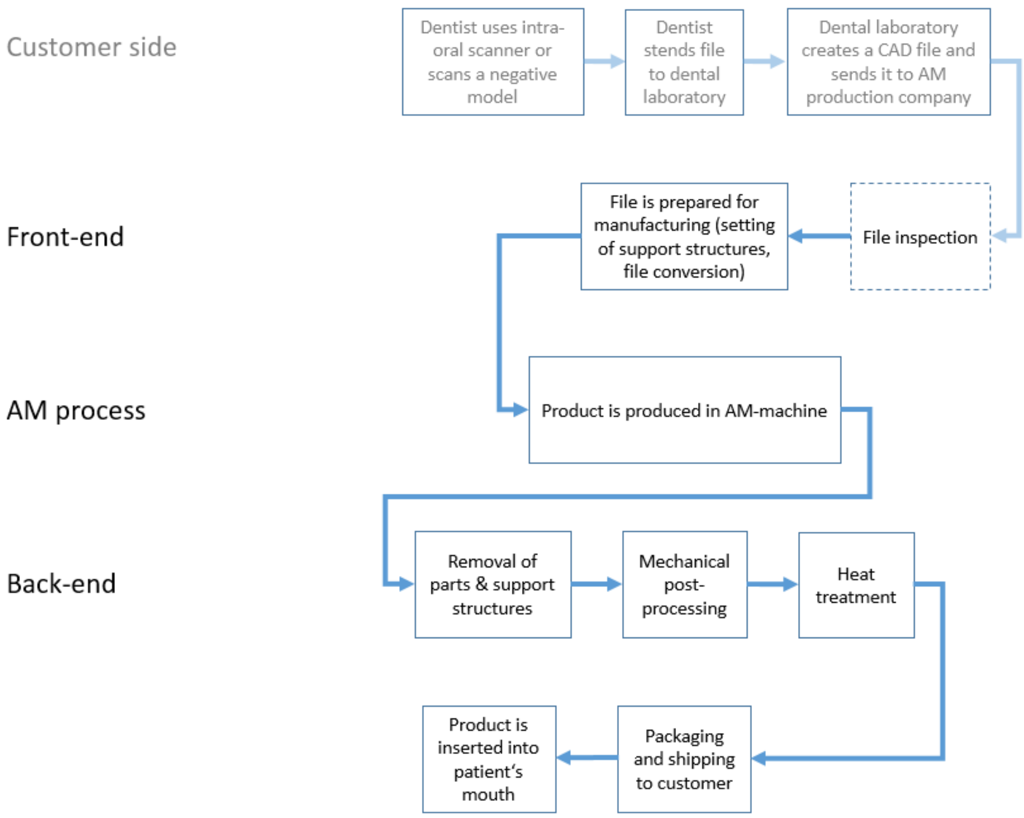

Figure 7: CAD/CAM process chain for dental products investigated

Figure 8 illustrates the different times each case company took to implement RM for MC.

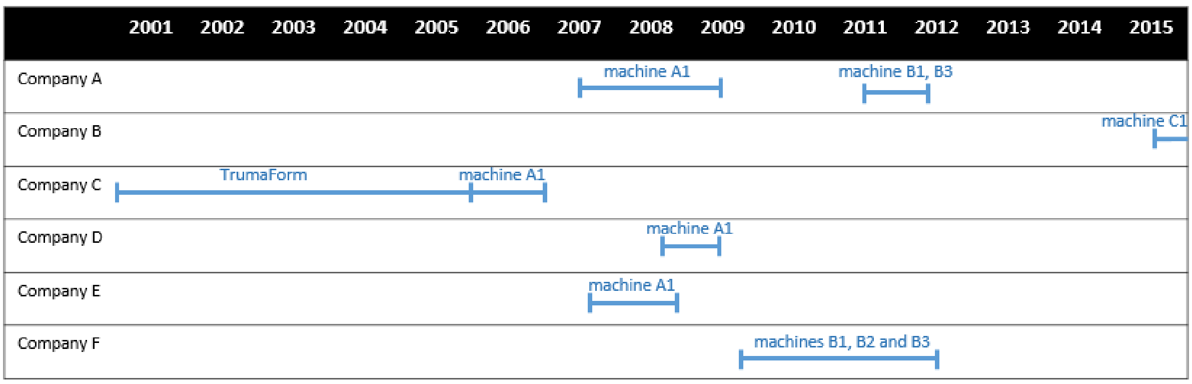

Figure 8: RM Implementation time line

While the pre-installation and installation phase lasted more than six years for Company C, the other five companies progressed to the post-commissioning phase within less than two years. Company B even managed to implement the full AM process with a semi-automated post-processing step for the milling part within eight months by acquiring the process technology from Machine Manufacturer C in 2015. Thus, most of the challenges during the installation phase for Company B were merely synchronising existing internal software and employees to the acquired technology. This trend is mirrored by Machine Manufacturer B entering the dental market later than Machine Manufacturer A and having to go through collaborative adjustments of their process and raw material together with Company F in 2009. Having developed the technology for the dental industry, implementation of RM for Companies A and D progressed significantly quicker and challenges were different in each implementation phase as will be shown in subsequent sections. Parameter adjustments and difficulties with powder are less relevant in later evolved models of Machine Manufacturer B's machines. Production planning is simplified by Machine Manufacturer B offering a smaller AM machine (B3) favourable to the dental sector.

Additionally, experience in digital dentistry appears to be another contributing factor with companies like Company A and Company B being able to implement the RM process at a quicker rate than companies without previous experience in this area.

Different dental products (also called 'indications') and its raw material requires R&D to adjust the software, AM process and post-processing and thus determines the technology maturity of the production process. As some regions such as the US are historically using different materials and indications – namely precious metals instead of CoCr – implementation of RM requires more R&D to adjust machine parameters and require more material accountability in these regions. As such, the pre-installation and post-commissioning phase for companies looking to implement AM seems to be more challenging since the requirements to achieve technology maturity are more complex. These results seem to show that technology maturity has an influence on how RM for MC is implemented and on the considerations and challenges observed.

Table 4 summarises the considerations and challenges regarding the overall process that the case companies regarded as most relevant to the success of the implementation process of RM for MC. Pre-installation and installation phases have been combined to reduce complexity as the acquired data overlap for both phases. Considerations that occur throughout all stages have been clustered separately. Only relevant insights that are not company specific and are observed by at least two of the case companies are discussed in this and subsequent sections. Aspects that may be relevant for RM implementation for MC despite being only named by one of the case companies will be included.

Table 4: Overall process related considerations and challenges

Technical (Overall process)	Considerations and challenges	Company A	Company B	Company C	Company D	Company E	Company F
Implementation stage							
Pre-installation, installation phase	• AM machine parameters had to be determined to adapt AM for RM of dental products			x			x
	• Setting up an identification system for product traceability was a challenge		x				
Post-commissioning phase	• Machine A2 was chosen because it allowed Company C to close down process parameter for its subsidiaries, thus ensuring uniform processes			x			
All implementation phases	• Machines with smaller build platforms were preferred because it increased manufacturing flexibility and speed of production	x		x			

Pre-installation and installation phase:

During the pre-installation and installation phase, Companies C and F as the first to implement RM for dental applications for their respective AM machines had to collaboratively research and adapt process parameters for dental application and high volume production together with their AM equipment manufacturer. Additionally, all companies had to set up an identification system to trace their products for documentation; only Company B specifically named this point to present a challenge during the early implementation stages.

Post-commissioning phase:

Process consistency is – apart from the above mentioned factors – dependent on the employees involved in the manufacturing process, according to Informant B (2015). AM, despite offering a more automated production method compared to casting methods used in the dental industry, still has several points where human interaction can be the cause of errors. File preparation, machine set-up between batches including sieving and cleaning, parts removal and post-processing present areas where process consistency in regard to product quality can be compromised. When expanding production abroad, Company C has therefore started using the A2 despite having to validate the AM process for dental applications internally. The A2 offers the possibility, apart from newer updates, to “close down” parameters for production centres abroad and to help standardise the production according to Informant AM1 of Machine Manufacturer A. Reducing the possibilities for employees to deviate from protocol increases process consistency (Informant A, 2015; Informant AM1, 2015).

All implementation phases:

The number of products in one batch depends on the size of units manufactured. As AM machines are limited in size, the number of units that can be produced in one batch depends on the size of the object. Additionally, subsequent processes such as powder sieving will require more time for larger objects as more powder is utilised. Thus, Companies A and C preferred AM machines with smaller build platforms because it increases the manufacturing flexibility and speed of the entire production process.

5.2.2 Front end factors

Table 5 captures the process front-end related considerations and challenges involved with RM for MC.

Table 5: Technical RM process front-end considerations and challenges

Technical (Front-end)	Considerations and challenges	Company A	Company B	Company C	Company D	Company E	Company F
Implementation stage							
Pre-installation, installation phase	• Software required significant labour input, esp. with software that did not display a high degree of automation (e.g. Magics); this posed an impediment for RM scale-up	x		x			
	• AM implementers had to perform adaptations to software such as creation of style files		x	x	x		
	• Close collaboration with Software Company S was crucial			x			
Post-commissioning phase	• Full automation was not possible so far; employees still had to at least perform visual verification for each unit file	x	x	x		x	x
All implementation phases	• -						

Pre-installation and installation phase:

All case companies except for Company B utilised Software S1 from Software Company S or were using the 'Magics' software from Materialise. Depending on the year of implementation Magics was used prior to Software S1. Company A and Company C were using Magics from Materialise during their installation phase in 2006 and 2009 respectively. Both companies found that the software required too much processing time per unit when scaling up production. It took too much time ("several hours" (Informant A, 2015)) to support a part with Magics. Informant A (2015) from Company A summarises the demand placed upon the software:

"…we don't have a lot of time to spend analysing parts. It is much more of a rapid flow through our process and because of that we had to minimise our interaction with those files and the software. We have to use software that allows us to quickly orient, support and create batches/runs for the machines."

Companies E and F have been using Software S1 from the very beginning and found that the challenges faced during the installation phase for the software were not significant.

The process of file preparation with Software S1 consist of three different steps:

1. Files have to be loaded into Software S1
2. Supports are automatically positioned
3. An employee checks whether supports have been placed correctly. If not, some supports have to be reallocated or removed. The employee bases this on his or her experience.

Companies B, C and D had to perform adaptation to software and found this aspect a challenge in the pre-installation and installation phase. Company B, for instance, is utilising its own software. Since it has been using a non-STL file format, Company B has had to work on exporting files into STL[1]. The transition presented a challenge for the company in the beginning but was resolved in the post-commissioning phase.

The large number of different indications in the dental industry and the need to develop a software program for each indication if MC is to be achieved, poses a challenge for software companies and additional costs for implementers. Additionally, in order to ascertain the full range of applicability the software has to be developed for each different AM machine. Informant S (2015) from a leading dental software company describes the challenge as follows:

"Dental is a bit trickier because you have more than just two models. In the hearing aid industry, you typically only have shells and moulds but in dental you have about 12 different dental indications plus you have a number of models that you use like orthodontics models, the articulation models, you have surgical guides and so on… Trying to do this fully automated can actually be quite tricky."

For Company C, which was the first enterprise to develop RM for MC in the dental sector close collaboration with software provider was crucial to realise a working RM system.

Post-commissioning phase:

Despite Software S1 offering a more automated file preparation than Magics with preparation times of approximately ten seconds per unit, full automation without any human interaction is not possible at this stage, as observed with almost all case companies (Table 5). Even during the post-commissioning phase, Informant A (2015) noted that his company still needs to allocate people to carry out the file preparation despite software companies claiming 'full automation':

"The ideal scenario that you get from Software Company 1 or anybody else selling you a product is: Optimise your parameters and you will never have to look at the part. But the reality is that you still have to look at every part and make sure the computer did a good job of guessing where those supports should be."

All implementation stages:

There were no considerations that were apparent in all implementation stages for front-end factors.

5.2.3 Machine related factors

Table 6 captures the AM machine related considerations and challenges involved with RM for MC.

[1] A widely used file format for AM

Table 6: Machine related considerations and challenges

Technical (Machine related)	Considerations and challenges	Company A	Company B	Company C	Company D	Company E	Company F
Implementation stage							
Pre-installation, installation phase	• Machine parameters had to be adjusted and the implementers had to be able to experiment with a machine that had an open platform. (AM suppliers offered that possibility)	x	x	x	x		x
	• Adoption of raw materials to the AM process was a big challenge	x		x			x
	• Early versions of AM machines had technical deficiencies	x		x			x
Post-commissioning phase	• -						
All implementation phases	• Maintenance/set-up times were labour intensive due to bad material accountability in AM machines	x	x	x	x	x	
	• Powder handling and recycling presented a challenge as AM machines were described as "leaky"	x		x	x		
	• Sieving system and maintenance was considered a challenge financially; it was too expensive for some companies to buy from AM machine producer; in-house development or third party services were required			x	x	x	

Pre-installation and installation phase:

Almost all case companies had to adjust machine parameters when implementing an AM machine; they had to be able to "experiment" with the machine which required an open platform in order to implement it for RM for MC.

The challenge for companies implementing RM for dental applications varied depending on how well the AM equipment manufacturer had customised the machine and the raw material for production of dental goods. Company F, for instance, was one of the first companies to use equipment from Machine Manufacturer B for dental applications. During the installation phase Company F had to adjust process parameters and help co-develop the usability of the raw material. When Company F started operations, Machine Manufacturer B's machines were not tailored to serve the dental sector which created technical implementation and operations problems. The machine producer did not offer powder specifically for the dental sector and had to co-develop a material and correct process parameters for the dental industry together with Company F.

"Judging from our experience, the process was not so trivial and had to be further developed. ...The quality of (dental) products were really bad. They only became acceptable for dental applications after we adjusted the process parameters together with Machine Manufacturer B." (Informant F, 2015)

Similarly, Company C first produced on an AM machine made by Trumpf (TrumaForm) from 2001 to 2006 but failed to fully implement RM for MC. Only later the company switched to the Machine Manufacturer A machine when tests proved that the machine is better suited for their purpose. As the pioneer for RM dental application the installation phase lasted over seven years before the company was able to scale up production of appropriate consistency. The company had to co-develop appropriate raw material with other companies. Company A attempting to utilise new material for dental applications similarly had to develop new material for the AM process. AM Machine Manufacturers A and B reacted to the customised requirements of the dental sector by producing machines more tailored for dental applications (better material accountability, smaller build platforms). Early versions of AM machines adopted for the dental industry, however, displayed technical difficulties for companies A, C and F (malfunctioning lasers, etc.).

The cases illustrate that despite AM manufacturers having developed AM machines for RM purposes before dental companies started implementing them, AM machines still require significant resource input to be customised and adapted to an RM for MC system. Even after customisation of AM machines for dental applications, companies still need to be able to modify machine parameters for production.

Post-commissioning phase:

There were no considerations and challenges that were identified that were only relevant in the post-commissioning phase.

All implementation phase:

One challenge that persisted even in the post-commissioning phase, was the powder handling and recycling. Machine A1 of AM Manufacturer A and machine B1 of AM Manufacturer B were described as "leaky" in regard to powder containment by companies A, C and D. A significant amount of powder needs to be removed manually with a vacuum cleaner after each production run. Hence, the challenge for Company A is to keep the machines free of powder and to minimise the time for powder removal and recycling. Similarly, Companies A-E noted powder removal to be a major challenge as the powder has to be removed after each run. This action takes both time for setting up the machine as well as costs for employees performing the cleaning operation and investment in vacuum cleaners and the sieving system. For Company B, on each build approximately 45 min is lost just on the sieving process to prepare the powder to be re-used for subsequent production. With only a build height of 18-22 mm Company B is already sieving for 45 min. If a process is used for non-dental applications with higher build rates, the sieving would take even longer.

A second challenge that was named by Companies C, D and E was the high equipment cost for sieving and monitoring and the high maintenance cost if all maintenance costs were to be performed by the machine manufacturers. Companies D and E, for instance, found the sieving system provided by Machine Manufacturer A to be too expensive and alternatively developed its own system. Almost all RM implementers only use the maintenance service of AM machine manufacturers for technically complex operations which cannot be executed in-house. Informant C stated that the costs for the maintenance contract with Machine Manufacturer A are significantly higher than the in-house maintenance costs:

5.2.4 Back end factors

Table 7 captures the process back-end related considerations and challenges involved with RM for MC.

Table 7: Technical RM process back-end considerations and challenges

Technical (Back-end)	Considerations and challenges	Company A	Company B	Company C	Company D	Company E	Company F
Implementation stage							
Pre-installation, installation phase	• Developing and setting of post-processing steps was a challenge	x	x	x	x	x	x
	• Ascertaining annealing parameters in particular was challenging	x				x	
Post-commissioning phase	• -						
All implementation phases	• Post-processing could not be fully automated because of the uniqueness of the products and the requirement for manual post-processing (e.g. sandblasting, milling); thus, high labour input was required	x	x	x	x	x	x
	• Post-processing presented a major cost factor	x	x	x	x	x	x
	• Manual support structure removal may risk damaging of parts				x		

Pre-installation and installation phase:

Setting up post-processing was identified as a major consideration and challenge in all our cases. The main reason is the requirement for labour input and difficulty of automating this part of the manufacturing process. Informant A expressed his wish for process improvement as follows:

"If we could have one major change to this whole process, it would be reducing or limiting the need for human intervention on the grinding of the parts after they come out of the machine."

The annealing step to reduce internal stresses from an AM-produced indication using heat treatment takes about eight hours. Depending on the size of the products and the size of the batch, parameters such as the temperature and duration of the process need to be adjusted. This becomes relevant especially when production is scaled-up. Companies A and E stated ascertaining annealing parameters was a challenge in the installation phase. Particularly for Company E as an SME this problem was only solvable through governmentally funded research projects with academic institutes.

Post-commissioning phase:

No particular considerations and challenges only pertaining to the post-commissioning phase were observed.

All implementation phases:

All case companies have tried to optimise post-processing as much as possible but found full automation to be impossible as every part has a unique shape. Informant C of Company C describes the situation as follows:

“Because of the time pressure, post-processing has been reduced as much as possible so that the time per unit spent is relatively short… Since this is a manual process, labour costs play an important role.”

Requiring the high labour input for post-processing is a significant cost factor for production in a high wage economy such as Germany according to all case companies. Post-processing is seen by Company C as one of the most pressing issues that inhibit production scale-up due to the need for trained personnel. Company E stated that post-processing (excluding heat treatment) takes approximately six minutes per unit but is highly dependent on the quality of training of employees. Company F states that about 35-40% of all manufacturing costs stem from costs associated with post-processing.

Manual support removal presents a risk to the produced goods as employees may damage the products according to Informants CM1, AM1 and D1.

5.3 Operational factors

Table 8 captures the operational considerations and challenges involved with RM for MC.

Table 8: Operational considerations and challenges

Operational	**Considerations and challenges**	**Company A**	**Company B**	**Company C**	**Company D**	**Company E**	**Company F**
Implementation stage							
Pre-installation, installation phase	• Design of production planning system that accounted for timely production was a challenge	x	x	x	x	x	x
Post-commissioning phase	• Planning for fluctuating daily and seasonal demand was a challenge and had to be accounted for	x	x	x	x	x	x
All implementation phases	• Short delivery times posed production planning challenges		x		x	x	x

Pre-installation and installation phase:

Operationally, the design of a production planning system that accounts for timely production presented a challenge for all case companies during the pre-installation and installation phase. As all companies promised its customers product delivery within a few days (average 48h), an appropriate production planning system that took into consideration the batch production principle of AM.

Post-commissioning phase:

Similarly, during the post-commissioning phase fluctuating daily and seasonal demand had to be accounted for in day to day production by all case companies.

All implementation phases:

Short delivery times posed production planning challenges for Companies B, D, E and F throughout all implementation challenges.

According to Informant D2 (2015), orders come in throughout the day, and it is challenging to predict the order volume and plan production accordingly:

“Demand during peak times can be three to four times as much as during low times.”

Additionally, all companies guarantee delivery of goods within 48-72 hours which creates additional pressure of having to process orders quickly. Thus, production planning and control systems as well as data management played a crucial for the implementation of RM for MC. Product design in the sense of utilising novel designs did not play a significant role.

5.4 Organisational

Table 9 captures the organisational considerations and challenges involved with RM for MC.

Table 9: Organisational considerations and challenges

Organisational	**Considerations and challenges**	**Company A**	**Company B**	**Company C**	**Company D**	**Company E**	**Company F**
Implementation stage							
Pre-installation, installation phase	• Human resources: Hiring qualified personnel with technical knowledge was a challenge			X	X		
Post-commissioning phase	• Availability of human resources could present limitation to production scalability (in particular regarding post-processing)					X	X
All implementation phases	• Size of the company was beneficial for covering high investment costs for RM implementation	X	X		X		
	• Size of the company forced company to collaborate			X		X	X
	• Production strategy: - Striving for automation	X	X			X	X
	- Prioritising speed of production and production flexibility	X		X	X		
	- Maximising machine utilisation		X	X		X	X

Pre-installation and Installation phase:

When scaling up production all case companies have had to retrain existing personnel or employ new technicians. Companies C and E, in particular saw this aspect as a challenge during the pre-installation and installation phase.

Post-commissioning phase:

Informant E sees the scalability of their production limited by getting enough qualified technicians to execute the post-processing step. Informant F noted one drawback of employing only dental technicians is the limited possibility of production expansion into other sectors.

All implementation phases:

The size of Companies A, B and D seems to offer advantages in implementing AM technologies for mass customisation purposes. These companies are able to invest in several AM machines and have the option of not having to run machines at high production capacity. This reduces the risk of full production downtime in case of a machine break-down and of fulfilling orders more quickly. These bigger enterprises utilise many resources and expertise from across the companies: The companies use their expertise with precious metals and its quality assurance department to make products meet standards. Company B, for instance, was able to implement AM significantly faster than the other case companies. Its size allowed it to purchase a working process and to integrate it into an existing structure that accommodated digital manufacturing systems such as CNC milling: Technicians familiar with subtractive production processes could be retrained and existing digital processing systems could be adapted to incorporate RM. Companies C, E and F on the other hand relied on collaboration with external parties such as academic research institutions or industrial partners (AM manufacturer, raw material providers, software companies, etc.) to implement RM for MC. Company E and Company F, for instance, had to use collaboration to adapt the heat treatment for production scale-up.

The case companies prioritised different aspects in their production strategy. Companies A, B, E and F prioritised reducing human interaction and striving for automation. These companies take research initiatives even after the post-commissioning phase to automate further sections of the process such as post-processing.

Since AM represents a batch production method, companies have to prioritise between maximising their production capacity for each build or realising shorter production times by executing orders even if machine capacity is not maximised. Companies have to choose which of the two aspects they prioritise: Company E, for instance, having two AM machines opts to wait with the production of incoming orders until a certain number of units is reached before utilising their second AM machine. Companies B and F have a similar approach and usually operate at approximately 80 percent capacity. Company A and D apply a different production strategy. The company's priority is to produce units as quickly as possible and is willing to run all their machines at a lower unit production level. Generally, Company A operates the machines at 25-30% of production capacity:

"Instead of running 200 parts at a time, maybe we'll run 50 or 60 parts at a time... So we try to minimize the size of the runs that we have. That's the best way for us to get parts out of the door as quickly as possible." (Informant A, 2015)

Company B attempts to adopt both strategies by introducing a "production fast lane" that executes urgent and critical orders while the majority of the production is only executed when the batch size has a high number of built orders.

5.5 External factors

Table 10 captures the external considerations and challenges involved with RM for MC.

Table 10: External considerations and challenges

External	Considerations and challenges	Company A	Company B	Company C	Company D	Company E	Company F
Implementation stage							
Pre-installation, installation phase	• Customer acceptance of AM products presented a challenge	x	x	x		x	
	• Collaboration with other companies was crucial		x	x			
Post-commissioning phase	• Dental labs/customers were reluctant to outsource production	x					
All implementation phases	• Collaboration with external partners (universities, other companies) was absolutely necessary as resources and capabilities did not allow for in-house development and implementation	x			x	x	x

Pre-installation and installation phase

Customer acceptance of AM produced objects is a challenge that all companies have had to address. Depending on how well AM is established at a given implementation point in time and region, companies have to face this challenge to a different degree. Companies A, B, C and E found customer acceptance to be a challenge when implementing RM for MC. Informant A (2015) describes the attitude of dental laboratories in the US towards AM products as follows:

"Delivering to them (dental laboratories) a product that is slightly different to what they are used to seeing - it may function exactly the same, but it may look slightly different - is challenging, and continues to be challenging."

The criticism towards AM that RM implementers have to face seems to be more pronounced when the traditional method of production has already been an automated process (such as the milling of frameworks) according to Informant B (2015)

Company C distributed AM produced dental products with poor quality before 2006 and thus created a negative image of RM for dental applications in Germany. RM implementers who already had to educate the market and customers, had to address even greater scepticism. Informant AM1 (2015) describes this development in the following words as follows.

"The technology (AM) was introduced in 2001 by Company C for testing…at the time, however, with insufficient quality. That generated the prejudice which five to six years later were still to be found in the market that AM does not fulfil the requirements set by the dental market."

The case companies had to offer workshops and free samples of additively produced dental products to convince the dental market of the new technology. Informant E (2015) describes the repercussions of the introduction of insufficient quality products thus:

"Because of that it took us a lot of time and partly also money because we often offered test-objects which we did not charge them to persuade the customer of the quality of AM products. And that took us years (to recover).'"

The reason for RM being more established in Europe than in the US according to Informant AM1 is because the material Cobalt-Chrome (CoCr) with which most AM machines work was already established in Europe. The market did not have to accept a new material which played a role in the acceptance of AM products.

Post-commissioning phase

Company A faced the challenge during the post-commissioning phase that American dental companies were reluctant to outsource production.

All implementation phases:

While Companies B and C only relied on collaborations with industrial and academic partners during the pre-installation and installation phase, the other case companies had to collaborate throughout all implementation phases.

6 Conclusion and future work

The objective of this paper is to increase understanding of how RM is implemented for MC. Additionally, the research sought to identify considerations and challenges involved with RM for MC in the dental industry. The case results have provided insights into how companies implement metal RM for MC in the dental sector by elaborating on the most relevant implementation considerations involved. Section 5 also identified and summarised the commonly occurring and most prevalent challenges involved with such an undertaking for the investigated companies.

The case studies show the way dental companies implement RM for MC as well as that the considerations and challenges for implementation vary between the pre-installation/installation and post-commissioning phase as defined by Voss (1988). Additionally, the observed considerations and challenges of RM implementation for MC vary depending on the level of technology maturity. The cases suggest that the speed and way of implementing RM for MC as well as associated challenges can be different for companies implementing RM at later stages in time as suggested by Frohlich (1998) for advanced manufacturing technologies such as AM. Thus, existing implementation frameworks as proposed by Mellor et al. (2014) and Deradjat and Minshall (2015) may not be best suited to illustrate considerations involved with implementing RM for MC.

Our study identified 26 considerations and challenges which can provide the basis of understanding the issues associated with RM as an enabler for MC. Specifically, the findings contribute to a gap in literature identified by Fogliatto et al. (2012) on MC enablers in manufacturing by providing insights into how companies have successfully implemented RM to realise an MC approach. The cases show that RM enables MC in manufacturing to the highest degree of customisation, namely of 'pure customisation' according to Lampel and Mintzberg (1996), in which every product is unique and tailored to the customer while attaining mass production like output numbers.

The identified considerations and challenges can benefit practitioners in the dental industry seeking to realise MC with metal RM by taking into account the highlighted considerations and challenges.

The research is limited by the fact that it provides insights from only six companies of different sizes and from different geographies. Additionally, inherent drawbacks associated with a case study based approach as discussed by Yin (2009) are applicable. Generalisability of the conclusions is thus limited. Our results have revealed the challenges of implementing RM of metal products for MC in the dental industry. Future work may include a similar study of the dental industry in a few years to validate the identified challenges and conclusions with a greater sample size. Executing a similar study for other applications and industries in the future may provide the basis for comparative analyses of implementation of RM for MC and support the development of generalisable guidelines.

7 References

ASTM. (2012), “Standard Terminology for Additive Manufacturing Technologies”, ASTM Standard.

Atzeni, E., Iuliano, L., Minetola, P. and Salmi, A. (2010), “Redesign and cost estimation of rapid manufactured plastic parts”, *Rapid Prototyping Journal*, Vol. 16 No. 5, pp. 308–317.

Atzeni, E. and Salmi, A. (2012), “Economics of additive manufacturing for end-usable metal parts”, *The International Journal of Advanced Manufacturing Technology*, Vol. 62 No. 9-12, pp. 1147–1155.

Bateman, R.J. and Cheng, K. (2006), “Extending the product portfolio with ‘devolved manufacturing’: methodology and case studies”, *International Journal of Production Research*, Vol. 44 No. 16, pp. 3325–3343.

Davis, S. (1987), “Future Perfect”, *Reading*.

Dean, J.W., Yoon, S.J., Susman, G.I., Science, S.O. and May, N. (1992), “Advanced manufacturing technology and organization structure: empowerment or subordination?”, *Organization Science*, Vol. 3 No. 2, pp. 203–229.

Deradjat, D. and Minshall, T. (2015), “Implementation of additive manufacturing for mass customisation”, in Pretorius, L. (Ed.), *IAMOT 2015*, Cape Town, pp. 2079–2094.

Duray, R. (2011), “Process Typology of Mass Customizers”, in Fogliatto, F.S. and da Silveira, G.J.C. (Eds.), *Mass Customization. Engineering and Managing Global Operations*, Springer, London, pp. 29–44.

Duray, R., Ward, P.P.T., Milligan, G.W.G. and Berry, W.W.L. (2000), “Approaches to mass customization: configurations and empirical validation”, *Journal of Operations Management*, Vol. 18, pp. 605–625.

European Commission. (2003), “EU recommendation 2003/361”, European Commission, Brussels.

Federici, T. (2009), “Factors influencing ERP outcomes in SMEs: a post-introduction assessment”, *Journal of Enterprise Information Management*, Vol. 22 No. 1/2, pp. 81–98.

Fogliatto, F.S., da Silveira, G.J.C. and Borenstein, D. (2012), “The mass customization decade: An updated review of the literature”, *International Journal of Production Economics*, Elsevier, Vol. 138 No. 1, pp. 14–25.

Frohlich, M. (1998), “How do you successfully adopt an advanced manufacturing technology?”, *European Management Journal*, Vol. 16 No. 2, pp. 151–159.

Gibson, I., Rosen, D. and Stucker, B. (2010), *Additive Manufacturing Technologies*, Springer, New York.

Hart, C.W. (1996), “Made to Order”, *Marketing Management*, Vol. 5 No. 2, pp. 10–23.

Hayes, R.H. and Wheelwright, S.C. (1979), “Link Manufacturing Process and Product Life Cycles”, *Harvard Business Review*, Vol. 57, pp. 133–140.

Herriott, R. and Firestone, A. (1983), “Multisite qualitative policy research: Optimising description and generalisability”, *Educational Researcher*, Vol. 12 No. 2, pp. 14–19.

Holmström, J., Partanen, J., Tuomi, J. and Walter, M. (2010), “Rapid manufacturing in the spare parts supply chain: Alternative approaches to capacity deployment”, *Journal of Manufacturing Technology Management*, Vol. 21 No. 6, pp. 687–697.

Hopkinson, N., Hague, R. and Dickens, P. (2006), “Introduction to Rapid Manufacturing”, *Rapid Manufacturing - An Industrial Revolution for the Digital Age*, John Wiley & Sons, Ltd, Chichester, UK, pp. 1–4.

Informant A. (2015), “Interview. Implementation engineer and business developer. Company A”.

Informant AM1. (2015), “Interview. Machine manufacturer A”.

Informant B. (2015), “Interview. Lead process engineer. Company B”.

Informant D2. (2015), “Interview. Lead Production Manager”.

Informant E. (2015), “Interview. Head of Production. Company E”.

Informant F. (2015), “Interview. CEO and head of production. Company F”.

Informant S. (2015), “Interview. Lead programmer mass customisation projects. Software Company S”.

Khajavi, S.H., Partanen, J. and Holmström, J. (2014), “Additive manufacturing in the spare parts supply chain”, *Computers in Industry*, Vol. 65 No. 1, pp. 50–63.

Krajewski, L., Ritzmann, L. and Malhotra, M. (2007), *Operations Management - Processes and Value Chain*, Pearson Prentice Hall, Upper Saddle River, New Jersey.

Kruth, J.-P., Levy, G., Klocke, F. and Childs, T.H.C. (2007), “Consolidation phenomena in laser and powder-bed based layered manufacturing”, *CIRP Annals - Manufacturing Technology*, Vol. 56 No. 2, pp. 730–759.

Lampel, J. and Mintzberg, H. (1996), “Customizing Customization.”, *Sloan Management Review*, Vol. 38 No. 1, pp. 21–30.

Mellor, S. (2014), *An Implementation Framework for Additive Manufacturing*, University of Exeter.

Mellor, S., Hao, L. and Zhang, D. (2014), “Additive manufacturing : A framework for implementation”, *International Journal of Production Economics*, Vol. 149, pp. 194–201.

Mumtaz, K. and Hopkinson, N. (2010), “Selective Laser Melting of thin wall parts using pulse shaping”, *Journal of Materials Processing Technology*, Vol. 210 No. 2, pp. 279–287.

Munguía, J., de Ciurana, J. and Riba, C. (2008), “Pursuing successful rapid manufacturing: a users’ best-practices approach”, *Rapid Prototyping Journal*, Vol. 14 No. 3, pp. 173–179.

Pham, D.T. and Dimov, S.S. (2001), *Rapid Manufacturing: The Technologies and Applications of Rapid Prototyping and Rapid Tooling*, Springer, London.

Pham, D.T. and Dimov, S.S. (2003), “Rapid prototyping and rapid tooling—the key enablers for rapid manufacturing”, *Journal of Mechanical Engineering Science*, Vol. 217 No. 4, pp. 1–23.

Piller, F.T. (2008), “Observations on the present and future of mass customization”, *International Journal of Flexible Manufacturing Systems*, Vol. 19 No. 4, pp. 630–636.

Piller, F.T., Moeslein, K. and Stotko, C.M. (2004), “Does mass customization pay? An economic approach to evaluate customer integration”, *Production Planning & Control*, Vol. 15 No. 4, pp. 435–444.

Pine, B. (1993a), *Mass Customization: The New Frontiers in Business Competition*, *Harvard Business School Press*, Harvard Business School Press, Boston.

Pine, B. (1993b), “Making mass customization happen: strategies for the new competitive realities”, *Strategy & Leadership*.

Reeves, P., Tuck, C. and Hague, R. (2011), “Additive Manufacturing for Mass Customization”, in Fogliatto, F.S. and da Silveira, G.J.C. (Eds.), *Mass Customization. Engineering and Managing Global Operations*, Springer, London, pp. 275–289.

Ruffo, M., Tuck, C. and Hague, R. (2007), “Make or buy analysis for rapid manufacturing”, *Rapid Prototyping Journal*, Vol. 13 No. 1, pp. 23–29.

Saberi, S., Yusuff, N., Zulkifli, N. and Ahmad, M. (2010), “Effective factors on advanced manufacturing technology implementation performance: A review”, *Journal of Applied Sciences*, Vol. 10 No. 13, pp. 1229–1242.

Sandström, C.G. (2015), “The non-disruptive emergence of an ecosystem for 3D Printing — Insights from the hearing aid industry’s transition 1989–2008”, *Technological Forecasting and Social Change*, Elsevier Inc., Vol. 102, pp. 160–168.

Schroder, R. and Sohal, A. (1999), “Organisational characteristics associated with AMT adoption”, *International Journal of Operations & Production Management*, Vol. 19 No. 12, pp. 1270–1291.

Schroeder, R. (2007), *Operations Mangement - Contemporary Concepts and Cases*, McGraw-Hill/Irwin, New York.

Silveira, G. Da, Borenstein, D. and Fogliatto, H.S. (2001), “Mass customization : Literature review and research directions”, *International Journal of Production Economics*, Vol. 72 No. 49.

Stevenson, W. (2009), *Operations Management*, McGraw-Hill/Irwin, New York.

Tuck, C., Hague, R., Ruffo, M., Ransley, M. and Adams, P. (2008), “Rapid manufacturing facilitated customization”, *International Journal of Computer Integrated Manufacturing*, Vol. 21 No. 3, pp. 245–258.

Voss, C. (1988), “Implementation: A key issue in manufacturing technology: The need for a field of study”, *Research Policy*, Vol. 17 No. 2, pp. 55–63.

Weller, C., Kleer, R. and Piller, F.T. (2015), “Economic implications of 3D printing: Market structure models in light of additive manufacturing revisited”, *International Journal of Production Economics*, Elsevier, Vol. 164, pp. 43–56.

Welsh, J.A. and White, J.F. (1981), “A small business is not a little big business”, *Harvard Business Review*, Vol. 59 No. 4, pp. 18–32.

Westbrook, R. and Williamson, P. (1993), “Mass customization: Japan’s new frontier”, *European Management Journal*, Vol. 11 No. 1, pp. 38–45.

Wohlers, T. (2015), *Wohler Report 2015*, Fort Collins.

Wong, K. V. and Hernandez, A. (2012), “A Review of Additive Manufacturing”, *ISRN Mechanical Engineering*, Vol. 2012, pp. 1–10.

Yin, R. (2009), *Case Study Research. Design and Methods*, edited by Connely, S., 4th ed., SAGE Publications, London.