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Additive manufacturing at LEGO: Developing a holistic management framework for high-volume manufacturers

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Abstract

Additive manufacturing (popularly known as 3D printing) is developing rapidly these years becoming increasingly relevant to high-volume manufacturing firms. The additive nature of the production technique makes it distinct to traditional manufacturing techniques that tend to be less flexible. As a result, a separate research agenda for its business implications is needed. However, in spite of the increasing relevance and its scientific distinctiveness, prior research into the topic from the perspective of management science has been very sparse leaving both theorists and practitioners in a vacuum. The thesis is contributing to bridging this research gap by investigating the internal implications of additive manufacturing. More specifically, the focus is on the direct implications for operations and the indirect implications for product development and marketing. Due to the nascent nature of the research field, the study took an abductive approach where prior research was refined through an in-depth case study of the toy manufacturer The LEGO Group. Multiple qualitative approaches were utilized to develop the most holistic framework for additive manufacturing to date. The framework consists of 15 implications relevant for high-volume manufacturers when evaluating the potential of additive manufacturing. Finally, the implications were taken to a more abstract level showing how the common denominator of many of them is to lower the need for buffers.

Keywords: *Additive manufacturing, 3D printing, manufacturing, operations, supply chain, LEGO, industrial revolution, industry 4.0, buffers, variability*

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Glossary

Additive manufacturing (AM)
A manufacturing technique that adds materials together, typically layer upon layer, based on a 3D Model (ASTM, 2012). There are at least 15 different techniques categorized as additive (Redwood, 2018).

Additive manufacturing is popularly known as "3D printing" since many of the technologies share similarities to those of traditional inkjet printers. These similarities are most pronounced in hobby 3D printers, which use a technique with strong resemblance to printing since melted material is extruded through a moving nozzle. That said, many other techniques do not resemble traditional printing. Due to this, the term "additive manufacturing" (or simply "AM") will be used throughout the thesis since it is not printing but the additive nature that unifies the different AM techniques.

Buffers
Used to mitigate the variability in the production process. All variability will (unavoidably) be buffered by some combination of time, inventory and capacity. Time buffers work by delaying the product flow through the system. Inventory buffers work by storing extra products or work-in-progress to mitigate the irregularity. Capacity buffers work by having idle capacity to compensate for the variability. All buffers are costly and should hence be managed carefully (Hopp and Spearman, 2001; Hopp, 2008).

Lead time
Time between an order for an existing product is placed and its delivery to the customer. Lower lead time can make companies more responsive to fluctuating customer demand (Hopp, 2008).

LEGO
Short for The LEGO Group. Case company for the thesis and one of the biggest toy producers in the world.

Throughput time
Average time from when a production job is begun until it reaches a specific inventory point. Throughput time can be measured for a single production step or for longer processes. "High" or "increased" throughput time means that the processing speed is slow/has gone up (Hopp and Spearman, 2001).

Time to market
Time it takes from the development of a new product is initiated and until the product is introduced on the market. Often increased due to the development of tools for production. Lower time to market can make companies more responsive to react to shifting trends and customer tastes (Slack et al., 2016).

Traditional manufacturing
Used to describe currently dominating manufacturing techniques such as molding, drilling, carving, etc. Techniques are primarily formative or subtractive and specialized, leading to high economies of scale but also inflexibility, strict design restrictions plus expensive and time-consuming tooling (the process of creating and installing the tool needed for manufacturing) (Berman, 2012; Bianchi and Åhlström, 2014).

Variability
Degree to which a group of entities are nonuniform. Variability can both be controllable, e.g. due to many products, or random, e.g. due to unforeseen demand spikes (Hopp and Spearman, 2001; Hopp, 2008).

1. Introduction

Additive manufacturing has been glorified as a game-changing technology that could heavily impact manufacturing firms. But in spite of the hype, manufacturers have few tools to evaluate the operational opportunities and challenges of this technology. In this section, a brief introduction to additive manufacturing and its unique nature is given. Then, the thesis will turn to the empirical and theoretical problematization of the topic before outlining the purpose and research question of the thesis. The section will end with reflections regarding delimitation of the thesis.

1.1 Why additive manufacturing is different

Additive manufacturing (AM) is well described by first defining traditional manufacturing. Traditional manufacturing is typically subtractive or formative. Subtractive techniques produce objects by melting, carving, cutting, drilling, etc. excess material away from a larger piece of material (e.g. carving wood planks into a table). Formative techniques use molds or dies to shape the desired object (e.g. molding a plastic fork). Both techniques produce waste, have strict design limits and require expensive tooling and setup why they are best suited for high-volume production where economies of scale drive down unit cost (Berman, 2012; Bianchi and Åhlström, 2014).

AM is completely different by nature. AM is a broad term referring 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). Simply put, the technique does not subtract material or form material in order to create the final product. It adds material together based on a 3D model.

This subtle distinction is key because the additive nature makes it possible to overcome many of the downsides of traditional manufacturing. Since material is added rather than subtracted, the amount of waste is limited. Since no tools or set-up are needed, except for a 3D model, fixed costs are highly reduced. Also, design complexity becomes less expensive since complicated parts (e.g. hollow light-weight parts) can easily be built without any post-assembly (Berman, 2012; Nyman and Sarlin, 2014; D'Aveni (A), 2015).

Due to the variety of techniques and design flexibility, AM has already become industry-standard in product development enabling developers to create better and faster prototypes at a fraction of former costs (Cohen et al., 2014; Mellor et al., 2014).

1.2 Problematization

The potential of AM goes however far beyond rapid prototyping. The true potential lies in actual production of end-products. Until recently, the quality and costs of AM limited the use to product development, but in recent years, the technology has progressed considerably. The progress and the variety in developed techniques described previously have spurred more and more firms to use it for actual end-production (Cohen et al., 2015). These AM use cases span different industries. For instance, the sportswear firm Adidas has invested in the AM firm Carbon3D and plans to produce 100.000 shoe soles in 2018 using their Continuous Liquid Interface Production technology (Carbon3D Inc., 2017). Another example is GE that has managed to bring down the weight, increase strength and reducing assembly for several parts of their jet-engines (D'Aveni (A), 2015).

The introduction of AM in rapid prototyping was driven by the economic and design advantages described previously: No tooling costs, design freedom and no assembly. Companies like GE and Adidas are now hoping to reap the same benefits – but for high-volume end-products. These investments in AM by highly influential companies may be a signal that many other firms might follow suit in order to both reduce operational costs and enable new product designs that are unthinkable or too expensive using traditional manufacturing techniques.

However, empirically, this does however lead to two key issues. First of all, manufacturers need management tools to evaluate whether this new manufacturing technology is actually useful for them. This evaluation cannot be done simply by comparing the cost of printing a unit vs. molding it, for example. The company must take all aspects of its operations into consideration and analyze key questions: Will AM require new suppliers? Will product quality be compromised? Can we produce new products that were previously not possible? Will we need the same operational setup as today? Tools to investigate the potential impact from a macro level will be valuable for senior management trying to bridge different parts of their organization.

Second, additive manufacturing has mostly seen usage for end-production in industries where customization of products is highly valued, e.g. in the hearing-aids industry (D'Aveni (A), 2015). But most manufacturers are not producing customized products. As Holweg puts it, *"… we also know that 99% of all manufactured parts are standard and do not require customization"* (Holweg, 2015, p. 2). An empirical question arises from these "99%". Will mass-producers benefit as well, or is the AM a party reserved for a limited group of companies where customization is key?

From a theoretical point of view, the understanding of how manufacturers will be impacted seems limited as well (Ford et al., 2016). First of all, most research dealing with AM has been done within the spheres of computer science, material science and healthcare. There is very limited literature exploring the managerial effects of AM in general (Ben-Ner and Siemsen, 2017; Weller et al., 2015). Second, this limited body of research is often quite split. Some scholars praise the technology and list many benefits but few potential downsides. They are very optimistic when it comes to AM's potential for manufacturing firms but do not really distinguish between different industries and product types (Berman, 2012; D'Aveni (A), 2015; Schwab, 2017). In contrast to these optimistic views stand more pessimistic scholars claiming that AM is overhyped and will not have as profound consequences as claimed. They tend to emphasize the potential downsides and pay little attention to the potential upsides (Bonnín Roca et al., 2017; Holweg, 2015). Third, in spite of a couple of initial frameworks investigating benefits, implementation issues and economic consequences (Bianchi and Åhlström, 2014; Mellor et al., 2014; Weller et al., 2015), there is still no management framework addressing the operational impacts of AM for manufacturing firms. No scholars have thoroughly managed to synthesize and structure the numerous arguments regarding AM implications found in the current body of literature.

1.3 Purpose, contribution and research question

The purpose of the thesis is to provide a more thorough understanding of what the internal implications of AM might be for manufacturing firms. More specifically, it will investigate how high-volume producers will be affected from an operational standpoint. The overall aim is to synthesize the current body of literature and combine it with in-depth findings from the thesis' own research. Through this work, the thesis will contribute with a more holistic understanding of how mass-producers internally are affected by AM.

The main research question will focus on the direct operational impacts, while two complementary sub-questions will investigate the indirect implications for the two other core functions of any company; product development and marketing (Slack et al., 2016). The complementary questions serve to produce a more detailed analysis and a broader scope for potential internal implications of AM. The main research question and sub-questions are as follows:

RQ1: How will additive manufacturing benefit and challenge operations of high-volume manufacturers?

RQ1.1: What will the indirect implications for product development be?

RQ1.2: What will the indirect implications for marketing be?

1.4 Delimitations

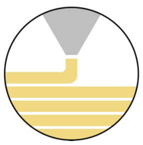
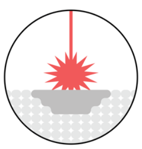
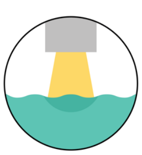
Given that AM potentially affects more than one thesis can cover, delimitations are needed. The most important delimitation will be not to examine the external competitive environmental impacts of AM. This aspect is relevant in the discussion of whether or not AM will lead to fundamental changes in the competitive landscape. Several scholars and especially the popular press have claimed that people in the future could download a design and print their own objects instead of going to a store (Berman, 2012; Weller et al., 2015; Rayna and Striukova, 2016). Other scholars see it going the opposite way with more centralized production capacity through gigantic generic factories able to manufacture toys Monday, guns Tuesday and car axles Wednesday (D'Aveni (A), 2015).
Such changes would significantly affect the overall business strategy of manufacturing firms heavily and potentially lead to less vertical integration and lower barriers of entry. However, within the limited scope of a master thesis, covering this aspect in detail was not prioritized.
Instead, the focus will be exploring the internal aspects of manufacturing. Specifically, the thesis will investigate how AM affects the operational aspects of a company, meaning how it is creating and delivering its products (Slack et al., 2016). Operational issues will be the starting point of the analysis, but the related core functions of a firm, product development and marketing, will be analyzed when the operational impacts of AM indirectly affect them. The specific issue of how AM can be used for prototyping will also be largely ignored since it is already well-described and industry-standard in the majority of manufacturing firms (Cohen et al., 2014; Mellor et al., 2014).

To sum up, the thesis treats external competitive strategy as exogenously given. Instead, the focus will be on how AM can impact company operations making sure they deliver on their strategy. Furthermore, the thesis will restrict itself to manufacturing firms producing high-volume products. Other industries are relevant too, but the current limited research has mainly discussed industries where low batch sizes or customization is a prerequisite. As mentioned previously, the aim of thesis is to expand the knowledge base of the vast part of manufacturing where mass-production is key. AM also poses bigger societal dilemmas regarding intellectual property, gun control, etc. These topics, relevant as they might be, will neither be the focus of the thesis.

2. A brief overview of AM technologies

Most people know AM from hobby 3D printers, but AM is far from just one technology. At least 15 different technologies have been developed since the 1980ies (Redwood, 2018). Illustrating the variety in materials and techniques, a brief overview of the five main categories is as follow.

Table 1: Categories of Additive Manufacturing

	Category	Technologies	Materials	Description
	**Material Extrusion**	• Fused Deposition Modeling	• Primarily plastic	Strings of solid thermoplastic is melted in the nozzle and extruded onto a build platform. The plastic solidifies again as it cools down, and another layer can then be applied on top until the desired object is reached. Fused Deposition Modeling is the most widely used technology since it is used for hobby 3D printers.
	**Powder Bed Fusion**	• Selective Laser Sintering • Selective Laser Melting • Direct Metal Laser Sintering • Electron Beam Melting • Multi Jet Fusion	• Plastic • Metal	A thin layer of powder is spread over the build platform. This layer is melted/sintered by a thermal source, typically a laser or electron beams, before a new layer is applied on top.
	**Direct Energy Deposition**	• Laser Engineered Net Shape • Electron Beam Additive Manufacture	• Metal	Thin layers of metal (metal strings or powder) are dispensed and melted by a thermal source, typically laser or electron beams. The technique can move more freely around which is very useful for repairs of existing components. The technique is however not efficient for producing parts from scratch.
	**Material Jetting**	• Material Jetting • Nanoparticle Jetting • Drop on demand	• Plastic • Metal • Wax	Drops of material are dispensed through multiple (potentially hundreds of) nozzles on the build platform. The material is then solidified using either UV light (plastic), high temperatures within the build platform (metal) or simply harden by itself (wax). The process shares many similarities to inkjet printers.
	**Vat Photopoly-merization**	• Stereolithography • Direct Light Processing • Continuous Liquid Interface Production	• Plastic	A tank of liquid photopolymer (plastic resin) is exposed to a digital light projector or a laser with a specific wave-length. The light triggers a chemical reaction which solidifies the plastic the exact places exposed. This continues layer upon layer until the desired object is reached.

Note: Based on overview by Redwood, 2018. Two minor categories are left out.

3. Theory

This section begins with a brief section on why a separate AM research agenda is needed followed by the overall characteristics of the current body of AM literature. The literature review continues with a synthesis of the potential AM advantages and challenges found in the current literature and ends with outlining the theoretical gap. Based on the synthesis and the gap, the theoretical framework will be conceptualized in order to provide guidance for the rest of the thesis.

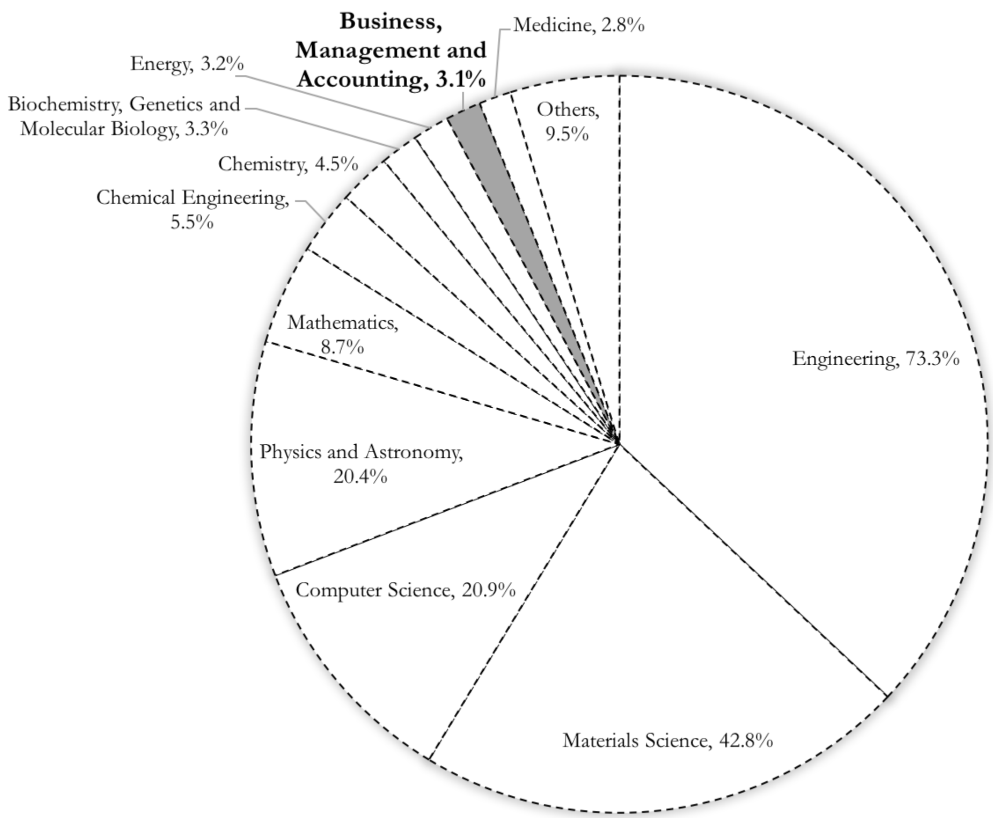
3.1 Literature review

Research into manufacturing systems of flexible nature is not a new phenomenon why readers might question whether a separate AM research agenda is even needed? The short answer is yes (Mellor et al., 2014; Weller et al., 2015).

The additive nature of the production technique does not only challenge traditional manufacturing techniques from a technical perspective, it also challenges traditional manufacturing from a scientific perspective. Some of the most established practices within operations management are built around the properties of current manufacturing techniques (Holmström et al., 2016). Inventory management is built around long lead times and long distances between production and usage. Factory setup and scheduling is based on the need for many production and assembly steps. Batching is based on the assumption of economies of scale. All these practices might need revision due to the fundamental difference in technical and economic properties of AM (Mellor et al., 2014; Weller et al., 2015; Holmström et al., 2016).

But in spite of the need, the separate business research agenda is still very nascent. There is a growing academic attention for AM, but this has primarily been driven by research within engineering, materials science, physics, computer science, design and health care. However, research on the business implications of AM is however still rare (Bianchi and Åhlström, 2014; Weller et al., 2015; Oettmeier and Hofmann, 2016). A categorization of the 11.200 search results for AM in the academic database Scopus illustrates the sparse amount of AM literature within business, management and accounting.

Figure 1: Categorization of AM literature



Note: Search on "Additive Manufacturing". Retrieved from Scopus.com May 7th, 2018. Each source can relate to more than one topic why sum can exceed 100%.

3.1.1 Operations in focus

As mentioned above, the thesis will focus on how AM impacts on operations rather than how it impacts overall business strategy. The thesis defines "operations" in line with Slack and Lewis (2002) who see operations as "(…) *the part of the organisation where the requirements of the market and the capabilities of the organisation's resources have to be reconciled*" and operations strategy as "*the total pattern of decisions which shape the long-term capabilities of any type of operation and their contribution to overall strategy*" (Slack and Lewis, 2002, pp. 4–14). The operational understanding is hence broad enough to capture the core processes leading to the delivery of the product but narrow enough to keep focused on how operations help delivering on overall business strategy, but not what the overall business strategy should be.

This does not mean that the overall business strategy is never affected by operations. A good business strategy would always be affected by the operational capabilities and challenges of the organization (Slack et al., 2016). But for the thesis, the operational capabilities will be the focal point.

3.1.2 Structure of the review and choice of sources

The review will be structured in a thematic way (University of North Carolina, 2018), where sources are reviewed around topics rather than journals, chronology, etc. More specifically, the aim will be to contextualize and synthesize arguments regarding operational implications of AM. Many "pioneers" within AM research have dealt with the operational aspects indirectly and put forward arguments regarding implications. However, due to the novelty of the research agenda and the rapid technological improvements over the last years, a complete overview does not exist. Furthermore, most research touches only vaguely upon each argument leaving out relevant nuances and counter-arguments.

However, examining the extant literature, it is clear that some coherence has started to occur. These instances of coherence will form the themes structuring the review. Furthermore, since the arguments relate to implications, many authors (e.g. Campbell et al., 2011; Bianchi and Åhlström, 2014; Weller et al., 2015; Ford and Despeisse, 2016) list them as either negative or positive – presumably since neutral implications are of minor empirical relevance. The thesis will follow in line and categorize the themes around a simple dichotomy of potential advantages and potential challenges. A total of 18 themes have been identified; 11 potential advantages and 7 potential challenges.

Sources for the review have been chosen based on talks with professors, PHD scholars, practitioners, database research, citations in other sources and the total amount of academic citations. More than 100 sources have been screened, and from these, 25 have been included in the actual review of advantages and challenges. They are primarily journal articles, but due to the novelty of the field, a number of magazine articles, book chapters, conference papers and reports from practitioners have also been included. The sources have been chosen since they deal primarily with operational consequences. Most of the sources rejected were focused on strict technical or overall strategical issues.

3.1.3 Potential operational advantages from AM

3.1.3.1 No tooling cost

The most celebrated advantages of AM are related to the low or non-existing tooling costs. 22 of the 25 sources deal with this particular issue. AM technologies do not depend on expensive tools or complex machinery set-ups. The only new elements needed are a 3D model and potentially a change in material. This dramatically lowers the costs related to shifting production from one product to another. Traditional machines often require unique and extremely expensive molds, drills, etc. for each individual shape. The change itself also takes time, often several hours, lowering the efficiency of the factory and creating opportunity costs. Furthermore, many AM machines are significantly more flexible than most traditional manufacturing systems meaning that one AM machine could potentially do the job of several traditional machines lowering invested capital needs (Berman, 2012; Nyman and Sarlin, 2014; Weller et al., 2015; Ben-Ner and Siemsen, 2017).

The flexibility and lower costs related to set-up and tooling are an advantage to all manufacturing firms. But the biggest advantage could be to enable more companies to produce low volume series without excessive costs. Since there are no or few costs related to shifting between product series, one of the biggest factors of economies of scale are off-set. Some scholars are even talking about constant unit costs (Ben-Ner and Siemsen, 2017). These developments enable manufacturing firms to follow strategies that were not feasible before. First and foremost, it lowers the barriers to pursue long-tail strategies. Long-tail strategies are characterized by companies selling many different products in low volumes to many different segments instead of or as a supplement to just addressing the need of large customer segments with high volume standardized products (Anderson, 2006). Long-tail strategies are nowadays often expensive due to the fixed costs related to each product series, but AM could make long-tail strategies feasible to more companies because of the lower fixed costs (Piller et al., 2015).

Taking it a step further, AM could lead to mass-customization of products. Mass-customization *"… is defined through a certain sort of contradiction. By assumption, it should join advantages of single piece production (individually and precisely) and mass production (quickly and in-expensively). Its implementation is highly attractive from a client's point of view, but it is a significant hindrance for a company and brings a risk of failure, especially as a result of increase of design and manufacturing costs. (…) MC allows fulfilment of the expectations of every client by adjusting a product to the client's needs"* (Zawadzki and Żywicki, 2016, p. 106). Without any tooling and set-up, the only prerequisite needed to produce customized products will simply be an updated 3D model (Bianchi and Åhlström, 2014; Mellor et al., 2014; D'Aveni (A), 2015).

In sum, a lot of the business interest in AM comes from the fact that the technology diminishes the influence of scale and opens up the opportunity to target even the smallest customer segment – potentially single individuals.

3.1.3.2 Greater design freedom

Traditional manufacturing techniques put constraints on which structures to build, what properties to achieve and which materials can be combined. AM on the other hand is not put under such restrictions. By adding materials "layer by layer," it is possible to create complex designs without going through costly steps of double-molding or assembly (Campbell et al., 2011; Ford and Despeisse, 2016; Oettmeier and Hofmann, 2016).

The first benefit of the greater design freedom is that geometric complexity becomes cheaper. This can lead to many types of new or redesigned products. Objects can be created in new geometric shapes that enhances their strength but have in the past been too complex to produce. Many of these structures can qualify cheaper materials to substitute for traditional materials used, in construction for example. Additionally, the advanced geometric structures enable hollow objects that remain strong but become more lightweight. This is an advantage to all products that are transported over long distances, but especially in industries such as space and aviation where part weight is essential. Complex structures can also make it possible to create porous objects in which liquid can be stored, or where air can better ventilate to cool down the object quicker (Weller et al., 2015; Ford and Despeisse, 2016; Oettmeier and Hofmann, 2016; Ben-Ner and Siemsen, 2017).

The second benefit is the possibility of constructing objects from multiple materials. Using traditional manufacturing techniques, it is often costly or simply impossible to combine different types of colors and materials. AM techniques are however increasingly changing this. In 2016, an AM machine able to combine 21 different metals was revealed, and same year, a machine printing different types of plastic polymers in 360.000 different colors was launched (Hiner, 2016; Orcutt, 2016). This development can make it easier to give objects certain aesthetic features, e.g. multi-colored plastic objects, or physical features, e.g. stronger strength due to the combination of materials. But it also opens up possibilities to build wires and circuits straight into objects (D'Aveni (A), 2015; Ben-Ner and Siemsen, 2017).

Some AM scholars have claimed that complexity is essentially costless using AM techniques (Nyman and Sarlin, 2014; Weller et al., 2015). This has been criticized by many others that point out that there are still limits to what you can build. (Holweg, 2015; Bonnín Roca et al., 2017). If not completely free, complexity is still more inexpensive than using most traditional manufacturing techniques. This provides one of AM's most appealing traits. As Khorram Niaki and Nonino (2017) conclude, AM brings *"…not only a process innovation (…) but also product innovation*" (Khorram Niaki and Nonino, 2017, p. 70).

3.1.3.3 Part consolidation

Closely related is the potential advantage to consolidate the amount of parts used for each product; the greater flexibility in designs can make it possible to construct parts as one (or fewer) piece(s) instead of as multiple assembled pieces (Bianchi and Åhlström, 2014; Ford and Despeisse, 2016).

The part consolidation aspect has several benefits. It often contributes to lighter parts, and since there is no assembly, parts also tend to be more durable. This durability reduces the need for spare parts and maintenance. Moreover, this often makes it possible to eliminate multiple casting/molding steps and remove (or at least limit) the following assembly, reducing costs and the risk of assembly mistakes (Bianchi and Åhlström, 2014; Weller et al., 2015).
The most described case of part consolidation (and probably the most used AM example in general) is GE's fuel nozzles providing jet engines' combustion chamber with fuel. This highly precise part is now being produced using a powder bed fusion technique in one piece. GE manufactures approx. 45.000 each year and used to produce it by assembling 20 different subparts. With the new technique, they have managed to produce a stronger part at 25% of the original cost (D'Aveni (A), 2015).

3.1.3.4 Waste reduction

Another benefit from the additive nature is to reduce waste during production. Since most traditional manufacturing processes subtract material, their waste rate can be high. AM techniques on the other hand use almost only the material needed in for the end-product according to scholars (Campbell et al., 2011; Khorram Niaki and Nonino, 2017).

This is an advantage to all manufacturers since it can potentially lower the bill of materials, especially in certain sectors where the degree of waste is particularly high and/or materials are very expensive. A good example of this is the aerospace industry, in which waste rates are high and materials are expensive. The ratio of input material to final product is typically around 4:1 and for some complex parts as high as 20:1 (Ford and Despeisse, 2016).

3.1.3.5 Faster time to market

Time to market is "*the elapsed time taken for the whole design activity, from concept through to market introduction*" (Slack et al., 2016, p. 702). The adoption of AM for prototyping has already brought down the product development cycles. AM usage for end-products might help decrease the time to market even further. Since AM provides more flexible production capabilities and low tooling cost, the steps taken after a successful product design has been chosen can be reduced. As long as the company has enough AM capacity and am updated 3D models, it could be able to initiate production quickly after (Cohen et al., 2014; Weller et al., 2015).

Shorter time to market can be an advantage to most companies but especially to the companies in markets of rapid technological developments or shifting consumer trends (Waller and Fawcett, 2014).

3.1.3.6 Lower lead time

Related to faster time to market is the possibility of AM decreasing lead time. Lead time is defined by the time between an existing product or part is ordered and delivered to the user (Hopp, 2008). AM can enable this in two ways. First, it can simply be a result of the reduced or non-existing set-up time due to the lack of tooling. Second, the special properties of AM could make it possible to set up more localized and decentralized supply chains where products are produced closer to the customer.

Scholars mention that AM, in spite of having higher unit cost than large scale traditional manufacturing, can be leveraged to bring newly developed products earlier to the market because of the lower lead times. Since the tooling process and production set-up time can be long for traditional manufacturing techniques, AM can be used to "bridge" the demand and potentially gain market share in highly competitive marketplaces (Berman, 2012; Holmström et al., 2016).

3.1.3.7 Lower inventory

Closely related to lead time is AM's potential to reduce inventory levels. With lower lead time and a more responsive production capacity, the need for inventory to meet demand would be reduced. Instead companies would just need idle capacity and bulk input material available, leading to lower investments in inventory and hence lower need for capital, lower storage costs and lower risk of obsolescence (Berman, 2012; Waller and Fawcett, 2014; Khorram Niaki and Nonino, 2017). Some scholars even describe the possibility of "zero lead time" or "instantaneous inventory management" where all products are made instantly and to order (Nyman and Sarlin, 2014; D'Aveni (A), 2015).

Most companies focus on reducing their inventory levels (Hopp, 2008). But especially companies in industries with high demand uncertainty can benefit from this since it will be easier to respond quickly to demand in spite of being far from factories or inventories (Waller and Fawcett, 2014). A good example could be industries or organizations where spare parts are frequently needed such as airline companies or armies. For both organizations, it is currently very costly to ensure available spare parts (Campbell et al., 2011; Cohen et al., 2014; Kietzmann et al., 2015).

3.1.3.8 Reduced logistics

The current structure of many supply chains is based on the assumption of long and expensive tooling, specialized machines, multiple assembly steps and economies of scale (Ben-Ner and Siemsen, 2017). As described above, AM challenges these assumptions of traditional manufacturing and could give reasons for supply chains being reconfigured. Several scholars argue that AM will allow companies to keep production closer to the end-market since the benefits of centralization will not be as big. This phenomenon is referred to as "localization" or "glocalization" (Bogers et al., 2016; Ben-Ner and Siemsen, 2017).

Aside from the already mentioned shorter lead time, the main benefit of a localization strategy will be reduced costs for logistics. This is both a consequence of a shorter distance from production to customer or retailer, but also due to fewer internal shipments to/from warehouses and assembly facilities. Furthermore, suppliers of raw material will often be available closer, and raw material can easier be provided more in bulk than particular parts for assembly (Ben-Ner and Siemsen, 2017; Nyman and Sarlin, 2014; Waller and Fawcett, 2014).

3.1.3.9 Upgradability

A few scholars are also arguing that AM will make it easier to upgrade or refurbish products. This is in stark contrast to current trends where most consumer products are just replaced with new ones, e.g. cars, clothes and smartphones (D'Aveni (A), 2015; Kietzmann et al., 2015; Holmström et al., 2016).

For manufacturing firms, this can enable new ways of serving customers. Instead of just selling new products, manufacturing firms could instead refurbish old products or sell continuous upgrades. It might even be possible to subscribe to a product and get continuous upgrades, similar to the way many software solutions are sold nowadays (Ford and Despeisse, 2016).

3.1.3.10 More sustainable

Some scholars are also seeing AM also as a more sustainable production method than traditional manufacturing (Campbell et al., 2011; Kietzmann et al., 2015; Ford and Despeisse, 2016). When considering the aforementioned benefits regarding logistics, material waste, optimized light-weight designs, longer durability and opportunity to upgrade products, the potential is quite clear.

Many of these advantages benefit companies from an economic standpoint, but they can also help companies achieve their CSR goals (Ford and Despeisse, 2016).

3.1.3.11 Digitalization driver

Many current manufacturing systems are partly or fully analog. It is not possible to receive or transfer data easily to these systems which limits the digitalization opportunities (Westerman et al., 2014; Schwab, 2017). AM technologies distinguish themselves from traditional manufacturing systems not only by being additive but also by being digital by nature. They depend on digital 3D models, and most of their processes are monitored digitally. Therefore, adopting AM technologies can hence be a way for companies to accelerate their general digitalization efforts (Campbell et al., 2011; Bianchi and Åhlström, 2014).

There are many operational benefits from a more digitalized supply chain (Slack et al., 2016). One of the most appraised benefits by AM scholars is the ability to use co-creation or crowd-sourcing when developing new products. This could enhance companies' R&D capabilities and lead to increased customer engagement (Cohen et al., 2014; Rylands et al., 2016).

3.1.4 Potential operational challenges from AM

3.1.4.1 Low quality

A main challenge for AM is the quality of the produced parts. The quality is simply not as good as that of traditional techniques where it has been refined for decades, sometimes centuries. Some of the most common quality issues are lack of dimensional precision and lower surface finish. This means that the produce might not look or have the properties that customers expect. Often the AM produced objects also have lower durability which can lead to breaks during usage. This is mostly due to a majority of AM techniques building "layer by layer" horizontally, meaning that most AM produced objects are stronger horizontally than vertically (Bianchi and Åhlström, 2014; Weller et al., 2015; Khorram Niaki and Nonino, 2017).

AM also suffers consistency of production issues. The ideal situation in which users are able to print the same item anywhere is not realistic when different printers and materials create variability (Bianchi and Åhlström, 2014; Oettmeier and Hofmann, 2016).

Quality has increased in recent years, but quality is still a significant challenge for AM. Quality issues can lead to either scrapped products or dissatisfied customers because of unmatched physical or aesthetic expectations. In order to meet expectations, more quality control may be needed, but this imposes further expenses on manufacturers (Baumers et al., 2016; Bonnín Roca et al., 2017).

3.1.4.2 Few and expensive materials

Another related challenge is the low variety of materials available for AM machines. Materials for traditional manufacturing have been developed over centuries, but the market for AM materials is still very immature. Much of the development for AM machines has been done by tech start-ups that do not necessarily possess the competencies to develop high quality and versatile materials (Mellor et al., 2014; Baumers et al., 2016).

The restricted range of materials limits the possibilities of what can be produced using AM techniques (Weller et al., 2015). Furthermore, the limited range available is often significantly more expensive compared to traditional materials. This is the consequence of a combination of the low demand for AM materials in general, and the lack of competition within the field. The result is materials that often cost 10 to 100 times more than materials used in traditional manufacturing (Berman, 2012; Khorram Niaki and Nonino, 2017). Holmström et al. (2016) exemplifies this beautifully by calculating the cost of printing the parts for a single small sedan, both metal and plastic parts. The cost ended at $357.000 (Holmström et al., 2016, p. 7).

The material selection is developing quickly, and prices are likely to decrease drastically as the demand and competition increases. But in spite of this quick development, AM still finds itself far behind traditional manufacturing techniques in terms of materials.

3.1.4.3 Low economies of scale

As mentioned previously, AM has the advantage of close to constant unit costs. This argument is not necessarily wrong as AM does provide low volume benefits. However, this argument also implies that the economies of scale for AM is low.

Inherently, this makes it difficult to use AM for high volume production since companies cannot reap the traditional benefits of mass production (Berman, 2012; Bianchi and Åhlström, 2014). Further, the idea of more localized production is heavily based on the assumption of close to constant per unit cost. But examining the manufacturing process more broadly, pre- and post-processing must be included. Pre- and post-processing is typically a significant part of the total cost of producing a product (e.g. packaging and quality control), and these processes typically do not have constant unit costs (Holweg, 2015).

3.1.4.4 Additional post-processing

Contributing to the problem of low economies of scale is the substantial post-processing associated with AM produced objects. AM often lacks behind when it comes to surface finish meaning that parts often require polishing or paint afterwards. Traditional manufacturing techniques have often been optimized to avoid this (Piller et al., 2015). Furthermore, the construction of AM objects often requires support material around the actual object while in production. This material will need to be removed afterwards (Campbell et al., 2011; Ford and Despeisse, 2016).

As mentioned previously, AM can consolidate the amount of parts and hence reduce the need for post-processing assembly. However, AM might pose new challenges for manufacturers when it comes to finishing the products.

3.1.4.5 High throughput time

Another major challenge is the speed of processing, also known as throughput time (Hopp, 2008). AM machines process objects slowly. This is challenging since companies would need numerous printers to reach the needed capacity, and it is going against the arguments of lower inventory and lower lead times (Campbell et al., 2011; Mellor et al., 2014; Nyman and Sarlin, 2014). Throughput should not be confused with responsiveness, an area in which AM is strong (as mentioned both when dealing with time to market and lead time). However, the high throughput time can reduce some of the benefits of high responsiveness. Airlines, for example, carry vast amounts of spare parts around the world's airports, and it would be highly attractive to just produce them on demand (Siemens AG, 2017). However, if it takes several hours to produce a new part, the opportunity costs of not flying would by far surpass the holdings cost of excess inventory.

Going back to the sedan example, Holmström et al. (2016) estimated that it would take 205 days to print the entire car using 2014 printers (Holmström et al., 2016, p. 7). Since then, printing speed has improved drastically by either improving speed or simply building multiple units in the build space at once (Abrams, 2015). But the speed of AM is still a concern when it comes to using AM for end-products.

3.1.4.6 Higher energy consumption

In spite of having several environmentally friendly characteristics, AM is criticized for higher energy consumption per unit compared to traditional manufacturing. Most of the techniques involve curing or melting of material, and the high-powered energy sources needed require large amounts of energy (Bianchi and Åhlström, 2014; Nyman and Sarlin, 2014; Khorram Niaki and Nonino, 2017). Specifically, powder bed fusion used for metals can be energy intensive, since it involves first creating the raw material, turning it into powder, and then melting it in order to create the final product (Mellor et al., 2014).

3.1.4.7 Fixed mindsets and lack of skills

Several authors point out how organizations might not be ready to leverage AM. As Bonnín Roca et al. (2017) state: *"Engineers (including us) have been trained on tools and approaches to design that are tailored toward conventional manufacturing. Training engineers to take advantage of the freedom that additive manufacturing will provide while understanding its limitations will require time. Indeed, limitations are still being discovered. In* *addition, the software tools that engineers are currently trained on may not be suited for additive manufacturing, and it is difficult to find faculty capable of teaching the new tools"* (Bonnín Roca et al., 2017, p. 58).

In short, organizations need to build whole new capabilities to take advantage of AM (Cohen et al., 2014, 2015). This poses a challenge because of fixed mindsets in many organizations. Many manufacturing firms are built from proud traditions and have optimized current manufacturing techniques. Enabling them to think more freely can be a big challenge (D'Aveni (B), 2015).

3.1.5 Theoretical gap

As should be clear by now, AM could bring both considerable advantages and disadvantages to manufacturing companies. However, the thesis would argue that a holistic overview for manufacturing firms is still missing for three reasons. First, most of the articles are based on limited empirical data. Since few companies have begun using AM, many arguments given tend to be theoretically based.

Second, thus far, no scholars have managed to capture all themes that have thus far been highlighted in the literature, and most are not close. As seen in table 2, many of the sources are only describing a very limited amount of the implications. This does not mean that the individual sources are bad since they might focus only on a few aspects deliberately. But if a manager or theorist wanted a full overview, it is currently not possible. It is quite telling of the state of the literature that the two most comprehensive sources is a report from 2011 (very old by AM standards) and an academic article primarily exploring AM from a sustainability standpoint (Campbell et al., 2011; Ford and Despeisse, 2016).

Third, when creating a proper tool to evaluate the implications of AM, the advantages and challenges needs to be structured properly. A couple of the articles have attempted to do so. Weller et al. (2015) try to formularize different economic implications of AM, but end up with a quite complex model that presumably will be too complex, especially for practitioners. Mellor et al. (2014) have constructed a framework for implementation which in many ways can be quite helpful to practitioners once they have taken the decision to implement AM. However, the framework does not help evaluating the potential implications of the technology. Finally, Bianchi and Åhlström (2014) have created the most holistic framework in prior research trying to describe how distinct features of AM and changed managerial features could benefit manufacturers. This framework is according to the authors however still "(…) *a first attempt to develop a managerial paradigm that supports the improvements enabled by additive manufacturing"* (Bianchi and Åhlström, 2014, p. 10).

In sum, few empirical studies of the impacts of AM have been conducted so far. Few scholars have written about the operational impacts, and those who have often only cover a few of the potential implications. And finally, no well-developed framework guiding the evaluation of AM implications exists.

Table 2: Overview of literature review

				Themes of potential advantages											Themes of potential challenges							
Author(s)	**Year**	**Type of source**	**Citations (Google Scholar)**	No tooling cost	Greater design freedom	Part consolidation	Waste reduction	Faster time to market	Lower lead time	Less inventory	Reduced logistics	Upgradability	More sustainable	Digitalisation driver	Lower quality	Few and expensive materials	Low economies of scale	Additional post-processing time	High throughput	Higher energy consumption	Fixed mindsets and lack of skills	**In total**
Campbell et al.	2011	Report	281	+	+	+	+			+	+		+	+	+	+		+	+	+		**13**
Berman	2012	Journal article	799	+			+			+					+	+	+					**6**
Bianchi & Åhlström	2014	Conference paper	5	+	+	+	+				+			+	+	+	+		+	+		**11**
Cohen et al.	2014	Magazine article	49	+	+		+	+		+				+							+	**7**
Mellor et al.	2014	Journal article	278	+	+		+			+	+					+			+	+		**8**
Nyman & Sarlin	2014	Conference paper	26	+	+	+	+			+	+				+	+	+		+	+		**11**
Waller & Fawcett	2014	Journal article	25	+			+	+	+	+	+											**6**
Baumers et al.	2015	Report	-	+	+																	**2**
Cohen et al.	2015	Magazine article	8			+		+		+	+										+	**5**
D'Aveni (A)	2015	Journal article	89	+	+	+				+		+					+					**6**
D'Aveni (B)	2015	Magazine article	-																		+	**1**
Holweg	2015	Magazine article	17	+	+												+	+				**4**
Kietzmann et al.	2015	Journal article	91	+						+	+	+	+					+				**6**
Piller et al.	2015	Book chapter	38	+		+					+							+	+			**5**
Weller et al.	2015	Journal article	195	+	+	+	+	+		+	+				+	+	+		+	+		**12**
Baumers et al.	2016	Journal article	135	+	+										+	+	+					**5**
Ford & Despeisse	2016	Journal article	129	+	+	+	+	+		+	+	+	+			+		+	+		+	**13**
Ford et al.	2016	Journal article	30	+	+																	**2**
Holmström et al.	2016	Journal article	24	+	+			+	+	+		+				+			+			**8**
Oettmeier & Hofmann	2016	Journal article	19	+	+	+									+	+						**5**
Rayna & Striukova	2016	Journal article	141	+										+		+	+					**4**
Rylands et al.	2016	Journal article	14	+	+		+		+	+				+	+	+			+		+	**10**
Ben-Ner & Siemsen	2017	Journal article	12	+		+			+		+					+						**5**
Bonnín Roca et al.	2017	Journal article	4		+										+	+	+	+			+	**6**
Khorram Niaki & Nonino	2017	Journal article	17	+	+		+	+	+	+					+	+	+			+		**10**
In total				**22**	**17**	**10**	**11**	**7**	**5**	**14**	**11**	**4**	**3**	**5**	**10**	**15**	**10**	**6**	**9**	**6**	**6**	

Note: "+" indicates that the given advantage/challenge has been described in the article. Google Scholar citations as of May 7th 2018.

3.2 Theoretical framework

The theoretical gap leaves significant room for a thorough empirical investigation into the implications of AM. But first, a theoretical framework building on the insights from the literature review will be developed. The theoretical framework will both be based on (Hopp, 2008) structuring of the study of supply chain operations and Slack et al.'s (2016) categorization of core corporate functions.

Hopp sees operations as a combination of processes and stock points needed to deliver the product to the customer. In this context, processes are the activities needed to produce and distribute the goods, while stock points are inventory places where these finished or work-in-progress goods are being kept, either deliberately or due to inefficiencies in the system (Hopp, 2008).
Based on this view, Hopp structures his investigation of supply chain operations into three categories; station science, line science and network science. Table 3 below defines each category using the authors own words and examples.

Table 3: Hopp's structuring of the study of supply chain operations

	Definition	Examples
Station Science	*"Considers the operational behavior of an individual process and the stock point from which it receives material. Our emphasis is on the factors that serve to delay the flow of entities (i.e., goods, services, information or money) and hence causes a buildup of inventory in the inbound stock point."*	Milling machine, bank teller, computer processing electronic orders
Line Science	*"Considers the operational behavior of process flows consisting of logically connected processes separated by stock points. We focus in particular on the issues that arise due to the coupling effects between processes in a flow."*	Manufacturing line, moving assembly line, sequence of clerks
Network Science	*"Considers operational issues that cut across supply chains consisting of multiple products, lines and levels. Of particular interest is the coordination of supply chains that are controlled by multiple parties."*	Inventory management, pooling, coordination

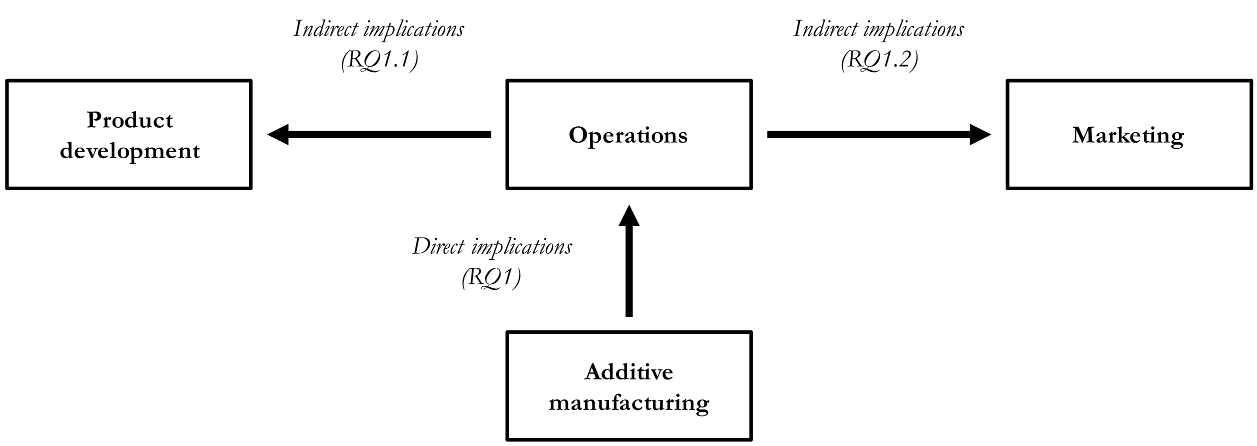
Note: Based on Hopp, (2008 pp. 7–9).

Hopp's trilogy, which distinguishes between operational stations, lines and chains, is beneficial to create structure around the identified advantages and challenges of why it will be used to structure the empirical investigation. However, Hopp's focus lies primarily on the creation of a product or a service. This focus makes the definition hard to apply outside the production setting.

This dynamic poses a problem for the thesis. As the research question and sub-questions indicate, many of the potential impacts of AM are not strictly limited to what happens at the factory floor. AM is a production technology, but since the thesis aims at building a holistic overview of the internal implications, other functions within the firm must be examined as well. The additional design freedom is a good example of this. It is an operational advantage since it makes it easier and cheaper to produce complex products, but it also opens up for designers to develop new types of products that were previously impossible either due to physical limitations or cost penalties. The theoretical framework hence needs to be broader.

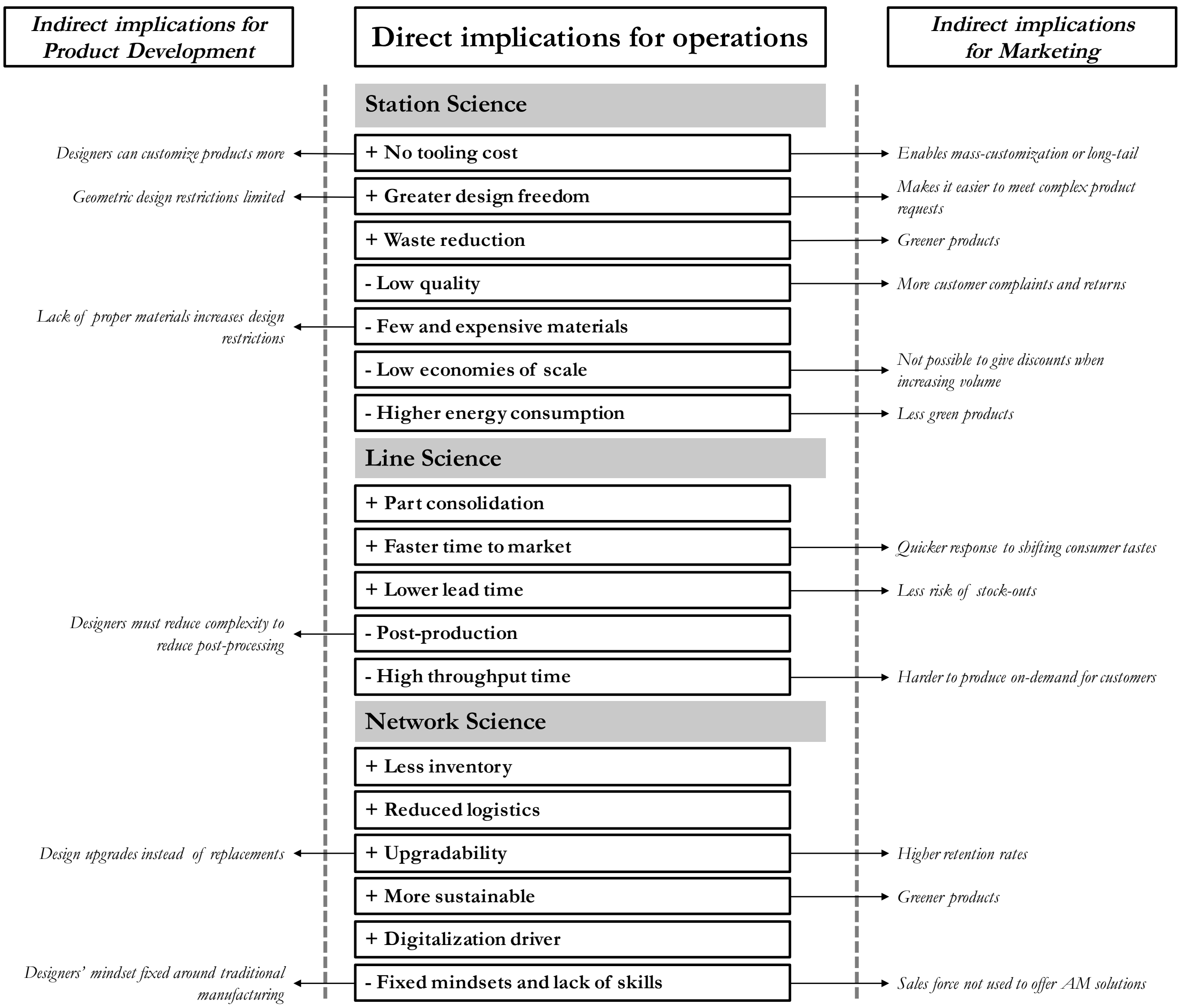
For this reason, Hopp's structure will be broadened beyond the mere production focus by including Slack et al.'s (2016) categorization of core functions in any company. These functions are the product development function responsible for generating new and modified products for future customer requests, the operations function responsible for creation and delivery of products for current customer requests, and the marketing function responsible for communicating with the market in order to generate customer requests (Slack et al., 2016, pp. 6–8). The operations function is similar to what Hopp is investigating with his trilogy of sciences, but the two other functions will add nuances to the framework when it comes describing the impacts of AM.
A visual representation of the theoretical framework linked to the research question and sub-questions are outlined below.

Figure 2: Visual representation of theoretical framework



As explained in detail in the methodology section, the thesis will take an abductive approach where an initial management framework derived from theory will be refined during the study (Dubois and Gadde, 2002). In line with this, the initial framework presented below synthesizes the literature review by classifying the identified AM implications around Hopp's trilogy and listing potential indirect implications. The empirical analysis will, through an iterative process described in the methodology section, investigate how it can be improved even further.

Figure 3: Initial management framework for AM implications



4. Methodology

This section will start by outlining the research design and approach, including considerations regarding research philosophy and methodological fit logically followed by my chosen research methodology and strategy. Then, the chosen case will be introduced followed by a section detailing data sources, collection and processing. Finally, perspectives regarding the quality of the study will be offered.

4.1 Research design and approach

4.1.1 Scientific approach and philosophy

After the literature review, it is clear that the body of AM research is fairly immature, or what Edmondson and Mcmanus (2007) calls a "nascent" state of prior research. This calls for rather open-ended research where the aim is to identify patterns and come up with suggestive theories (Edmondson and Mcmanus, 2007).

Due to this, the philosophy of the study will be interpretivist. Although the thesis focuses on a rather technical matter, interpretivism is needed to understand the broader implications on organizations as a whole. Ontologically speaking, it is not enough to simply describe how the machinery works. The thesis believes socially constructed and subjective impacts might exist. In line with this, the epistemological approach will be to only accept knowledge where the subjective organizational and managerial aspects are understood. The study is hence explanatory, or in the words of Weber, closer to *verstehen* rather than *erklären* (Saunders et al., 2009; Bryman and Bell, 2011).

In spite of being a nascent theory field, it has been possible to identify some coherence when it comes to the arguments presented by the initial AM scholars. However, the coherence is not widespread enough to test actual constructs in a deductive manner. The risk of "unknown unknowns" would simply be too large (W. Mullins, 2007; Saunders et al., 2009).

On the other hand, the study was grounded in some theory with the initial framework as a guideline as to why a purely inductive study could be avoided as well (Saunders et al., 2009). Instead, a more abductive approach was chosen. This was a way to leverage the existing work of prior researchers through a dialectic process using the framework as a guidance to both develop new knowledge and refine prior findings (Kovács and Spens, 2005). Dubois and Gadde (2002) refers to this as a "systematic combining process" and emphasizes that the theory both represents input and output of the research due to the "successive refinement of concepts" (Dubois and Gadde, 2002, pp. 557–559).

4.1.2 Methodological choice

In line with the characteristics of prior research and the chosen research approach, a qualitative approach was chosen for the thesis. Qualitative research is the best fit for nascent research field since it is a proper way to construct and refine theory rather than test it. At the same time, it provides a better opportunity to understand phenomena more in-depth in line with the philosophical considerations (Edmondson and Mcmanus, 2007; Bryman and Bell, 2011).

The thesis did not apply any quantitative means. This could have been a way to ensure higher external validity, but due to the immature state of prior research, it would have been risky to test any theoretical constructs without the threat of relations being spurious.

4.1.3 Research strategy

Since the thesis aims at refining scattered theoretical arguments and building a holistic management framework, the thesis was based around a single-case study. According to Eisenhardt and Graebner (2007), case studies are a good way to build theory and a way to bridge "*(…) from rich qualitative evidence to mainstream deductive research*" (Eisenhardt and Graebner, 2007, p. 25). This matches the goal of the thesis that primarily aims at creating constructs future researchers can leverage to move towards more deductive studies.

Furthermore, the strategy was to include multiple qualitative data sources in the analysis. This allowed for triangulation of data in order to increase confidence in the found results (Flick, 2009; Bryman and Bell, 2011). The variety of sources spanned wide and were even combined with approaches of ethnological character that can provide an insider's view on the investigated topic in a more informal and natural setting relative to other more formal techniques (e.g. research interviews). However, empirical data from these sources were utilized with caution for several reasons. The collection and interpretation relies heavily on the researcher, which makes it hard to impossible to replicate for others and to empirically create a proper trace of arguments throughout the analysis (Bryman and Bell, 2011). Due to this, the ethnological approach was primarily used as a way to guide the rest of the data collection, ensuring all relevant questions were investigated when using more traditional techniques.

Finally, a single-case study instead of a multi-case study was chosen for several reasons. The prime reason for this was the aspiration to go deep and *verstehen* potential implications in a specific setting rather than testing it across manufacturing companies (Saunders et al., 2009; Bryman and Bell, 2011). From a more practical standpoint, exclusive access was given to the single case chosen. The same exclusive access would have been hard to get from a broad range of companies, especially since it relies on a permanent presence of the researcher and the mutual trust between researcher and case company that it fostered.

4.2 The case company: The LEGO Group

The case company will be The LEGO Group (henceforth "LEGO"). LEGO is one of the world's biggest toy companies. Since it was founded in Denmark in 1932, it has sold billions and billions of its iconic bricks all over the world. In 2017, the company had 17.534 employees worldwide, net sales of $5.8B and EBIT of $1.7B equaling an EBIT margin of 29.6% (The LEGO Group, 2017).

LEGO represents a quite ideal case to investigate for the thesis. First of all, the company is a manufacturing firm specialized in mass-produced consumer goods. This qualifies it for investigating the outlined research question. Second of all, it controls both design, production and marketing of its products and even has its own brand stores. This makes it possible to investigate all parts of the theoretical framework. Third, the produced products are plastic pieces why AM could potentially be employed since AM, as outlined in section 2 is often used for production of plastic items.

From a more practical standpoint, the author was granted exclusive access to LEGO offering a special opportunity to conduct a deep dive into the company. LEGO remained the right to protect commercial secrets, but throughout the process, the author was given wide access to confidential material enabling the possibility to build holistic insights that could then be reported in a non-confidential format afterwards.

For disclosure, it is worth mentioning that no salary was paid for the thesis work. A final internal presentation will be delivered as part of the agreement.

4.3 Data collection & processing

4.3.1 Structure, sources and sample of the empirical investigation

The empirical investigation began with a pre-study. Coming only from a theoretical point of view, the aim was to understand how the practitioners at LEGO looked upon AM and how the sources should be sampled. This helped testing the research focus and prepare for the actual empirical investigation (Flick, 2009).

The pre-study included three elements. First, an interview with an internal expert on the company's value chain was conducted. A preliminary interview guide was created in order to test questions, but the interview was kept open-ended.

Second, the author was invited to attend an 8-hour workshop arranged by LEGO focusing on AM. This presented an excellent opportunity to get a broader introduction to the company and to the view upon AM from different entities since 20 employees attended.

Third, since the focus lies on a potential future production technology, it was very important to have a good understanding of LEGO's current manufacturing system. Due to this, the author was given access to the factory in Billund, Denmark, where LEGO is molding millions of bricks every day.

After the pre-study, the actual empirical investigation started. The prime empirical source was semi-structured interviews. In spite of having a lower repeatability, this data source was chosen since it allows the researcher to probe open-ended questions and improvise along the interview while still keeping some structure. Hereby, the researcher can access the interviewee's "subjective theory" including not only the explicit assumptions but also the implicit assumptions (Flick, 2009, pp. 156–161). Since interviewees came from different entities within the company, this technique was very valuable compared to other more structured interview forms because it made it possible to let them elaborate on parts relevant to their field of expertise. Three of the interviews during the actual investigation were however kept partly open-ended. The interviewees were specialists on AM, and the purpose was to receive feedback on findings why a more open-ended approach was found to be most adequate.

Face-to-face interviewing was preferred, but since LEGO is a global company, a large portion of the interviews were conducted via Skype. All interviews began with formalities regarding procedures and the permission to record the interview. The interview guide was designed with some initial questions that were quite open and almost off-topic in order to create trust between interviewer and

interviewee. After this, the guide turned towards some rather open questions related to the research question where nuances could be expressed. The interviewer then followed up with more theory-driven questions based on the initial framework in order to cover areas untouched through the more open process (Flick, 2009) (Interview guide is available in the appendix). The interviews averaged 57 minutes and lasted between 30 (interview unfortunately interrupted) and 70 minutes.
A total of 17 interviews were conducted. The interviewees came for different parts of the company and were selected through a purposive sampling technique where the author carefully chose interviewees who could help answer the research question. A more random sampling technique would not have been fruitful when the aim is to carefully refine theory through an abductive process. In line with this, sampling was done through an iterative process meaning that interviewees were contacted as the data collection progressed. This enabled the author to steer the sampling towards areas where saturation had not been achieved. Follow-up interviews were also used in case a couple of points remained unanswered after the data collection (Saunders et al., 2009).

The interviews were complemented different types of observations. First of all, the author conducted participant observations of a meeting and the aforementioned workshop. Observations can be a great tool to gather insights about the context and discover "delicate nuances of meaning" that are harder to get in the interview situation. The author was an active participant during the workshop. Since it was part of the pre-study, the target was to gather insights about sampling and create trust with potential interviewees rather than gathering flawless data. During the meeting later in the process, the author was passive in order to influence the interaction between employees as little as possible (Saunders et al., 2009, pp. 289–303). Since the thesis centers around a production technology, observation studies were also used to gain a broader knowledge of the physical processes of LEGO. As mentioned, the pre-study included a factory visit, but visits to two other test facilities were also conducted. This was a way to get a better understanding of the technical context of the thesis.
The author has also had access to LEGO's internal data system and plentiful of documents, plans, presentations, organizational descriptions, etc. This material has been confidential and cannot be showcased in the thesis, but it was helpful building background knowledge for the author.

Along with the other data sources, the author requested and was granted access to work alongside LEGO's team investigating how AM can be used by the firm. This allowed for an opportunity to conduct organizational ethnography where the researcher's possibility to understand the insider's point of view increases heavily (Bryman and Bell, 2011). The author spent a total of 24 days at LEGO's headquarters in Billund, Denmark, had a permanent desk in the office, ate lunch with the employees, etc. As a data source, the ethnographical insights cannot stand alone why other data sources have complemented it. But from a research standpoint, this agreement was invaluable. The author gained more trust and legitimacy than would have been possible as an external thesis student. Furthermore, it became easier to sample interviewees, gain access to senior employees and ask the right questions while interviewing.

Ethnographical researchers suffer from the risk of "going native" and being biased towards a favorable view of the subject studied (Bryman and Bell, 2011). The thesis has tried to avoid this by primarily always using data from the interviews in order to have a clear trail of evidence. Furthermore, LEGO's view on AM was quite neutral and functional; can we utilize it to gain advantages? Had the case company instead been a company selling AM technology, the risk of bias would have been larger.

The figure below summarizes the structure of the research process, and the table below provides a summary of the sources used in the thesis. Other pioneers within AM research have used case study methods as well (e.g., Bianchi and Åhlström, 2014; Mellor et al., 2014; Nyman and Sarlin, 2014; Ford and Despeisse, 2016; Khorram Niaki and Nonino, 2017). The author has however not found any other study presenting as in-depth a case study investigation within prior AM research.

Figure 4: Structure of the research process

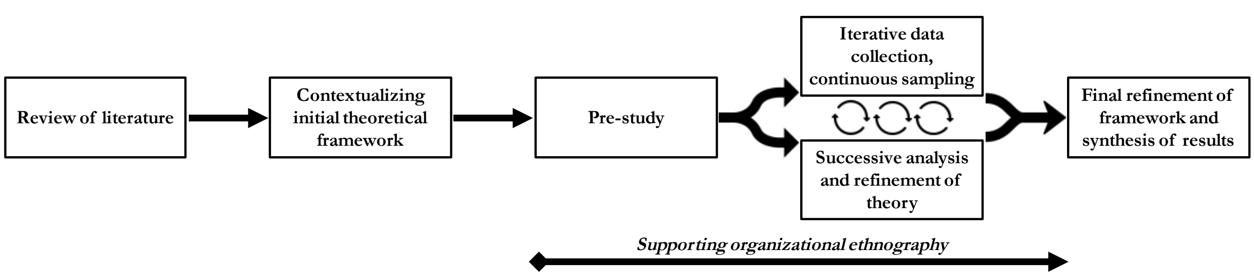


Table 4: Empirical sources of the thesis

Type	Number
Interviews	17, 13 semi-structured and 4 (partly) open-ended
Observations of employees	1 workshop and 1 meeting
Observations of production facilities	3 visits to facilities
Documents, presentations, plans, etc.	Numerous
Organizational ethnography	24 days spend at LEGO's headquarters

Note: Detailed overview of data sources can be found in the appendix.

4.3.2 Data processing

During the semi-structured interviews, notes were taken and the audio was recorded. Afterwards, they were quickly transcribed afterwards since this provided a good opportunity to reflect and iterate from continuously throughout the data collection process (Flick, 2009). To begin with, a quite open coding process was used to process the collected data. Over time, the coding list was structured and finalized, and all interviews were coded accordingly in order to secure consistency. Using an abductive approach, the coding list was modeled around the initial framework since the goal was to refine this. However, the coding list also opened up for new arguments still untouched by AM literature (Bryman and Bell, 2011). The coding list can be found in the table below. Each code consisted of two codes, a code related to Hopp's trilogy and an implication code, in line with the initial framework. E.g. statements dealing with how lead times could affect the sphere of line science would be marked "LINE/LEAD".

Table 5: Coding list

Science codes	Implication codes (advantages)	Implication codes (challenges)
STAT (Station science) LINE (Line science) NETW (Network science)	TOOL (No tooling cost) DES (Greater design freedom) PART (Part consolidation) WAST (Waste reduction) TTM (Faster time to market) LEAD (Lower lead time) INVT (Less inventory) LOGI (Reduced logistics) UPGR (Upgradability) SUST (More sustainable) DIGI (Digitalization driver) OA (other advantages)	QUAL (Low quality) MAT (Few and expensive materials) EOS (Low Economies of scale) POST (Additional post-processing) THRO (High throughput time) ENRG (Higher energy consumption) MIND (Fixed mindsets and lack of skills) OC (other challenges)

Insights from other data sources (observations, documents and organizational insights) were on a more ad-hoc basis synthesized in written form by the author. These insights were revised continuously to guide the prime data collection and refinement of theory.

4.4 Quality of study

4.4.1 Reliability

The reliability of any qualitative, especially those including ethnological approaches, will be challenged by the subjective evaluation of the researcher (Bryman and Bell, 2011). This is however mitigated in the thesis in several ways.

First, all data was gathered and coded by one researcher only why issues related to inter-observer consistency were non-existing (Bryman and Bell, 2011). Second, the collection and processing of interview data followed quite strict standards in order to secure procedural reliability (Flick, 2009). Third, multiple data sources allowed for triangulation that could increase reliability by comparing different types of data sources. The iterative sampling also aided in the same way by enlarging the "sample size" or ensuring saturation on topics where few insights had been made (Flick, 2009; Bryman and Bell, 2011)

Finally, all conclusions were drawn based on transparent empirical documentation, and not be based on something the researcher heard randomly passing by two employees (Flick, 2009).

4.4.2 Replicability

The thesis has aimed at being transparent in order to increase replicability. First of all, the research design has been thoroughly described. Second, main tools for the research process has all been presented, including interview sample, interview guide and coding list. This enables others to replicate the study. If not at LEGO, then at least in another setting (Bryman and Bell, 2011).

The replicability is however lowered due to the nature of the ethnographical elements. How do you replicate the relationships a researcher conducting ethnographical studies has built with the organization? These interpersonal aspects reduce the possibility of replicating the exact same study.

4.4.3 Validity

The internal validity of the study is deemed high. Yin (1994) argues that internal validity is less relevant for explorative studies such as the thesis since they do not test any specific causal

relationships. But despite being exploratory, the thesis will still investigate relationships between AM and relevant issues why spurious relationships could still be a threat to the validity of the thesis. The in-depth qualitative approaches and triangulation of sources are however a good way to ensure the internal validity why this is not seen as a problem in the thesis (Bryman and Bell, 2011).
The qualitative approach also strengthened the measurement or construct validity. It was easy for the author to elaborate questions and follow up on misunderstandings in order to make sure all constructs were fully understood by interviewees (Bryman and Bell, 2011). The organizational ethnography also ensured that found relationships were valid in the real world, increasing the ecological validity of the thesis (Bryman and Bell, 2011).

The external validity of the study is however low. With only one case, it is hard to generalize the findings outside the context of LEGO. This is however not the goal with the thesis. The study aims to build, synthesize and refine theory, and not to test it since the AM research agenda is too immature for that yet (Edmondson and Mcmanus, 2007; Eisenhardt and Graebner, 2007). If the study was replicated for multiple cases, it might be possible to rely on analytical generalization (Yin, 1994). But with the limited previous research, this is not possible for now.

5. Empirical findings & analysis

This section begins the refinement process of the initial management framework. To begin with, a brief overview of LEGO's current production setup and AM efforts will be presented. The theoretical advantages and challenges identified will then be revisited by presenting the empirical findings and analyzing the consequences. The theoretical advantages and challenges will be accompanied by insights not found in prior research but revealed during the empirical investigation. When quotes are included from different interviews, they are cited as I1, I2, etc.

5.1 LEGO's production and AM efforts

5.1.1 Current production

It is relevant to introduce LEGO's current manufacturing setup since it is a good example of the benchmark the thesis is trying to compare AM towards; traditional but heavily optimized and high-volume manufacturing.

LEGO's production has been optimized over decades making them very efficient and aligned. LEGO has factories in five locations across the globe. Most of the production is in-house, and the vast majority of the parts are made of plastic, primarily ABS thermoplastic polymer. This is done using traditional molding techniques.

The process begins with small pellets of plastic being delivered to the factory. The molding machines take in the pellets through pipes, heats them up and applies pressure. The mold is filled, cooled and then separated in order to free the bricks. These are still linked to each other due to leftover polymer. A robotic arm removes the leftover and places it in a grinder, granulating the plastic and feeding it back into the system eliminating almost all waste. The now detached bricks fall down on to a conveyer belt leading to a storage box on a scale. Once the weight corresponds to a full-box, a self-driving robot replaces it and drives the full to the storage facility. The storage facility is also fully automated with a robotic system storing all the bricks until they are ready for packaging or decoration. The steps of decoration and packaging are also heavily automated meaning that no human hand touches the individual bricks before it reaches the child (based on factory visit in Billund).

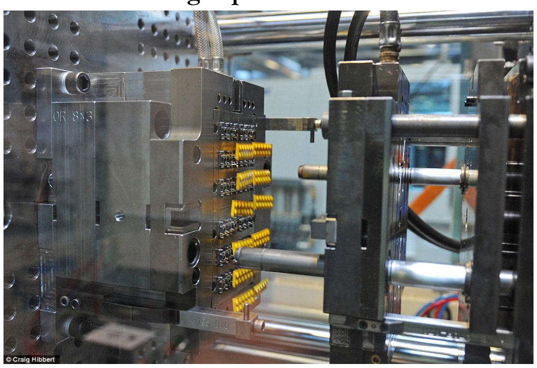
The above description is a simplified version but aims at illustrating that the system has been optimized heavily over decades. All processes fit nicely together making it highly efficient. This is relevant since this is what AM is up against – and not just at LEGO but at all high-volume plastic producers.

Figure 5: LEGO’s current manufacturing setup

Plastic pellets

Part of mold

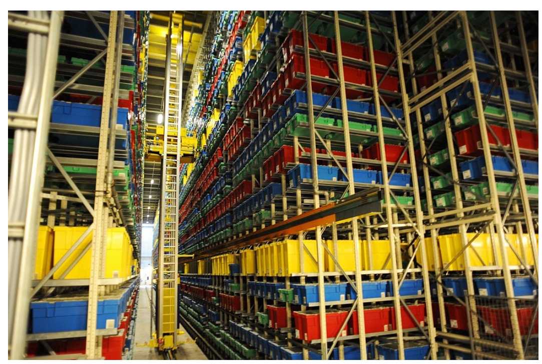
Two molds being separated



Coveyer belt

Self-driving robot picking up box

Warehouse



Note: Pictures from The LEGO Group (2018) and Daily Mail (2015).

5.1.2 LEGO’s work with AM

It is limited how much the thesis can disclose regarding LEGO’s work with AM. However, what can be revealed is LEGO’s use of AM for prototyping for 20+ years, making it an integral part of the new products development process. LEGO is not producing any end-products using AM techniques, but the company has a team of specialists researching how to leverage AM technologies.

This dynamic qualified the empirical data heavily since most interviewees already had done their initial reflections regarding the implications of AM.

5.2 Revisiting the potential advantages

5.2.1 Advantages within station science

Most interviewees mentioned the lack of tooling as a key advantage for AM. However, few interviewees focused primarily on the operational issues such as lower cost of production. They mainly focused on how AM could give new capabilities to empower customers relations. A reoccurring theme was how LEGO could better serve their retailers. As I7 explained, *"Retailers like to have a different assortment than their competitors. (…) AM could help us late-dedicate products and make them more unique, maybe even at the retailer's distribution center*."

Several interviewees also focused on how AM could make it possible to better target premium niche customer segments, as I3 explained. *"There will be a market, maybe even a premium market, with people who wants a [certain type of product], and then they want their name on it or whatever."* In line with this, I7 explained, *"We are not going after micro [trends], we are more for the macro ones where there is scale. Could AM help us go after micro ones as well? It could."*

From a product development perspective, AM could also loosen restrictions on designers, as I11 simply points out, *"Here is the challenge, we apply constraints based on the system"*.

A few interviewees were skeptical about the true value of customization itself. As I5 explained, *"You can customize products. But do people actually want customized product? How important is it for people and kids that products are unique?"* However, no one seemed to disagree that lower volume production could be made easier with AM.

Greater design freedom was also discussed during the empirical investigation. From a production standpoint, I2 summarized the advantages quite well by saying, *"AM can give us new shapes. The way a LEGO product looks right now is actually very much formed by what injection molding can do."*. From a cross-functional perspective, I6 also pointed to the fact that AM could be an advantage since today LEGO *"(…) put restrictions on the designers based on the production (…) We need to restrict complexity. But kids might request novel, cool elements. So, we can't restrict it too much."* I8 also confirmed that designers have designed elements that turned out to be too complex to produce and never became a reality.

Surprisingly to the author, the empirical study did not find waste reduction to be an advantage. This was due to the support materials often needed when building objects with AM. As I5 explained traditional systems where quite superior because, *"Support materials that are dissolvable in water, they cannot be recovered today. No AM suppliers have some sort of take-back system. (…) With traditional manufacturing, we have a circular system lowering cost and increasing sustainability."* According to I13, some AM techniques waste material while building, *"The print extruder is sometimes cleaned. (…) Some printer types explode in long threads before we start using them. And that cannot directly be reused."*

No other advantages within station science were found.

Table 6: Station science advantages

Code and theme	Primary finding(s)	Interviewees confirming	Exemplifying quote(s)
STAT/ TOOL (No tooling costs)	Major advantage, primarily to improve customer focus. I.e. better meeting retailer demands, creating "buzz" with special products, pursuing niche segments.	I1,I2,I3,I4,I5, I7,I8,I9,I11, I12,I13,I14, I15	• *"We could target niche customers groups and create buzz on internet and social media. I don't think it will be a big revenue source, but it could be a brand builder."*(I1) • *"Batch size 1 [using AM], the one end of the scale, does that work with a mass-producer? I think we need to consider that. Or at least move towards it."*(I9) • *"Small production runs also for unique elements would be possible (…) The cost of making unique elements is super high"*(I11)
STAT/ DES (Greater design freedom)	Advantage, enabling new possible designs and loosening up trade-off between complexity reduction and product innovation	I1,I2,I3,I5,I6, I8,I9,I11,I12, I13,I14,I15	• *"Our products are restricted today because they have to be able to leave the mold. With AM, you will not have that problem. You might have others, but it will give extra opportunities."*(I5) • *"You can produce things that are not possible on [a traditional type of machine]."*(I9) • *"Printing structures that are impossible. That's the first thing that pops into mind [thinking about AM]"*(I11)
STAT/ WAST (Waste reduction)	**Not** an advantage due to support materials and heavy waste	I5,I10,I12, I13,I15	• *"For AM, you need support structures and liquid afterwards to remove them. For powder beds, it is not as bad, but at some point, you cannot reuse the powder"*(I12) • *"Some of the printers use plastic platforms that cannot be reused. So, they are thrown out afterwards as well"*(I13) • *"Lego has almost 0% waste"*(I15)
STAT/ OA (Other advantages)	None		

5.2.2 Advantages within line science

LEGO might not be the most obvious company to investigate the advantage of part consolidation due to the nature of its de-constructed toys. Regardless, LEGO does produce some pre-assembled parts, including electronics, springs or different materials. However, the number of such parts is restricted today. I8 compared AM to the current setup and stated that *"[Assembly] adds to the price. With AM, we might be able to make things in one piece, that would be perfect"*. I3 also exemplified that price was not the only issue; "*Many years ago, we tried to mold circuits into the bricks, but it was too hard to scale."*

Almost all interviewees confirmed that time to market is something AM could improve. From a strictly operational standpoint, this could decrease development time. As I6 explained, *"Molds have a very long lead time (…) Especially for complex elements"*. But more importantly, AM would enable LEGO to respond more quickly to new trends, something that can be challenging with the current, less flexible system. As I4 exemplified: *"A couple of years ago, we moved a bit late on [certain movie]. What if we had the opportunity to do something much more quickly as soon as we saw the impact of the movie and knew what was happening?"*

In addition to faster time to market, many interviewees also agreed that lead time in general could be improved. The rationale is not that AM can compete with the production speed of traditional molding techniques but since it provides a lot of flexibility, AM can make the entire supply chain more agile as I7 illustrated: *"[A particular brick set] was selling like hot potatoes. But it ran out of stock because a particular part was not made available. (…) That's where AM could kick-in and make sure the sale goes through."*

I1 saw it as a way of creating a "*safety net*" to bridge when forecasting had been inaccurate. The same interviewee also explained that unique bricks and low-volume bricks had the longest lead time.

No other advantages within line science were found.

Table 7: Line science advantages

Code and theme	Primary finding(s)	Interviewees confirming	Exemplifying quote(s)
LINE/ PART (Part consoli-dation)	Advantage and something that is heavily restricted today	I1,I2,I3,I5,I8, I13,I14,I15	• *"[Process of assembly] requires very high-end equipment"*(I1) • *"You can part consolidate in ways not possible with injection molding"*(I5) • *"You can produce elements with functions and avoid assembly."*(I13)
LINE/ TTM (Faster time to market)	Major advantage since tooling and setup often slows heavily down the possibility to react to consumer trends	I1,I2,I3,I4,I5, I6,I8,I9,I13,I 14,I15	• *"People downstream are always puzzled: "Why does it take so long to produce a mold, we have already designed the element, how hard can it be?"*(I2) • *"There are examples in the past [of trends] where we chose not to pursue them because we felt it was a bit too late."*(I4) • *"From iterations to the market takes a long time (…) How do we then keep ourselves relevant when we have those restraints of the timeframe of both design and production."*(I8)
LINE/ LEAD (Lower lead time)	Advantage primarily by complementing traditional techniques when a certain mold/tool is not available for production or only a low volume of elements is needed	I1,I3,I4,I7, I14,I15	• *"Unique bricks (…) those bricks are often sitting with longer lead times, and they often hold us back from meeting consumer demand."*(I1) • *"You don't know exactly what to produce. What will sell? The later you can dedicate, the better. If you had a hall or containers with 3D printers that could be moved around to help molding facilities meet demand."*(I3) • *"We could use it as capacity when we see bottlenecks. Today, we put in buffers in order to mitigate demand fluctuations."*(I14)
LINE/ OA (Other advantages)	None		

5.2.3 Advantages within network science

Only a few interviewees saw inventory reduction as a potential advantage, including I3 who stated that, *"[With AM], I think we could really do something to the health of our stock. And it's a serious amount of money that is currently tied up in it."*

However, most interviewees do not mention it as an advantage. Primarily, they view AM more as a complementary tool helping to only produce a minority of special or needed parts rather than producing full brick sets.

In line with this complementary view of AM, the theoretical advantage of reduced logistics was generally not mentioned by the interviewees. Since they did not view AM as a replacement for traditional manufacturing, long-distance logistics from centralized factories would still be needed.

However, I4 admitted that *"tariffs and logistics is still a huge challenge*", and the same interviewee also believed that logistics could be reduced by creating mini-factories. But for this to happen, the mini-factory would have to produce all parts of the end-product.

The third network science advantage identified by the literature review is the upgradability. This advantage was neither confirmed nor denied by any interviewees. The main reason for this might be that LEGO's product is already upgradable or modular. This dynamic is the essence of LEGO's value proposition, which may be why this specific issue was not addressed.

LEGO is very concerned with sustainability, but none of the interviewees highlighted this as a distinct feature of AM. On the contrary, the issues with material waste makes AM less sustainable. As I2 explains, *"It is hard to imagine AM being more efficient and ecological than injection molding."*

Finally, some scholars saw AM as a way to drive digitalization within companies. Only one interviewee confirmed this was an advantage they had considered, meaning it was hard to reach saturation on this question.
However, the digitalization driver was closely related to an advantage not outlined after the literature review. Most interviewees agree that AM will be a supplement to traditional manufacturing today and in the near future, but looking even further into the future, it might become a viable competitor to traditional manufacturing. How will LEGO as a traditional manufacturing firm be able to respond to this? Many interviewees hinted directly or indirectly to AM as a way of preparing for a future where manufacturing might not be organized as it is today. As I3 said, *"Maybe in time, our product will not be boxes with bricks. Instead we might be selling printers, materials and guides?"*. And I4 followed asking, *"How can we leverage AM to a situation where people either have a printer at home or we have them in our distribution centers?*" Building up AM capabilities might be a way to answer these questions and prepare for future threats to traditional manufacturing firms.

Table 8: Network science advantages

Code and theme	Primary finding(s)	Interviewees confirming	Exemplifying quote(s)
NETW/ INVT (Less inventory)	Only minor advantage as long as AM is complementary	I1,I3,I7,I10, I15	• *"Maybe not taking down inventory that much, but maybe some of the complex and low volume parts that are quite expensive and hard to reuse."*(I10) • *"This inventory topic is not really a big advantage to LEGO currently"*(I15)
NETW/ LOGI (Reduced logistics)	Only a minor advantage as long as AM is complementary to current production	I4,I10	-
NETW/ UPGR (Upgrada-bility)	Case not proper to investigate this aspect	-	-
NETW/ SUST (More sustainable)	Not an advantage according to interviewees due to material waste	I2,I5,I10,I12, I15	• *"It could become, but definitely not today"*(I10) • *"Some techniques, you use ipropylalcohol and epoxy for the support structure. It is toxic!"*(I12)
NETW/ DIGI (Digitali-zation driver)	Minor advantage, but lack of saturation	I10	-
NETW/ OA (Other advantages)	AM could prepare the company for future competing business models and customer demands	I3,I4,I9,I10, I11,I13,I14, I15	• *"Maybe we can make it part of the customer construction experience to also build the parts themselves"*(I3) • *"In the future, there will be more democracy in design [due to AM]. Customers can be more involved in designing."*(I8) • *"AM could add a new experience to the product. (…) It opens up new business models for experiences"*(I11) • *"You cannot move an injection molding machine in a store. That's possible with AM. And people are quite fascinated by the process."*(I13) • *"With AM technology, we could maybe invite potentially 100.000 element designers [from our fan base]."*(I14)

5.3 Revisiting the potential challenges

5.3.1 Challenges within station science

As suggested by theory, the empirical findings confirm that quality is of concern to the employees of LEGO. AM cannot produce parts with the same consistency and surface finish as traditional molding techniques can, and some of the AM machines' output even look *"like a pile of hay"* according to I5. However, the quality of industrial printers has however increased dramatically over the last couple of years. As I2 explained, *"A year ago, the first concern would have been around quality of parts. Now we are getting past that assumption."*

As a toy manufacturer, LEGO is extremely cautious about the quality of the parts they produce. Almost all employees acknowledge that AM has to improve in quality before it can be used for end-products, but they are quite optimistic that this will happen. Also, most interviewees mentioned "lower" instead of "low" quality, an important distinction.

When it came to the supply of materials, the interviewees were more concerned. Those with more technical insights had significant concerns regarding the range of materials. As explained by I5, it often comes down to the fact that *"the AM providers deliver both machine and materials. And their portfolio is very limited for now."* This is according to the investigation the predominant business model of the AM suppliers; they sell input material for their own machines, restricting price competition and the development of new materials. I12 went as far as calling it a "marriage" to the supplier and illustrated the problem by saying, *"Imagine a CNC machine where the supplier said we only could use their steel. That would not make any sense at all."*

From a theoretical standpoint, the disadvantage of no economies of scale is one of the most emphasized challenges of AM. However, this was not mentioned by any of the interviewees as a concern. The reason seems to be that AM is still considered a complementary technology primarily used for low-volume batches. As long as this remains AM's primary function, the need to lower unit costs is limited.

On the topic of energy consumption, a few of the interviewees with technical experience agreed that the energy cost per part would probably be higher in the long run compared to the current setup. As AM is still viewed as complementary to traditional production, it was only considered a minor challenge. For smaller production runs, I12 also pointed out that the production of a mold had to be extremely energy intensive.

No other challenges within station science were found.

Table 9: Station science challenges

Code and theme	Primary finding(s)	Interviewees confirming	Exemplifying quotes
STAT/ QUAL (Low quality)	Challenge, but quality is improving very fast	I1,I2,I3,I5,I7, I8,I9,I10,I11, I12,I13,I15	• *"Some of the parts are getting to a stage where they can be sold."*(I2) • *"Technically, something is starting to happen now (…) But there is a long way from printers used for prototypes to end-products."*(I5) • *"I assume we will be able to solve it. You get far with money and time."*(I9) • *"Right now, we are really on a tipping point in terms of both volume and quality."*(I10) • *"Part quality, it is just a question of time. It will come."*(I15)
STAT/ MAT (Few and expensive materials)	Major challenge for several reasons; prices might be high, properties might be limited, and chemical composition is harder to evaluate for some AM techniques	I2,I5,I8,I10, I12,I13,I15	• *"You are often restricted to using the providers' own material."*(I5) • *"[Photopolymers] is a type of polymer that we are not used to. We do not know exactly how it behaves chemically"*(I5) • *"If you do not use their [the supplier's] material, and you get a problem with your machine, then they might try and say the failure is due to the material. So, you are sort of married to them"*(I12) • *"Most of the suppliers, they bind you to their materials."*(I13)
STAT/ EOS (Low economies of scale)	Not mentioned as a concern, presumably since AM is seen as a complementary technology	I10	-
STAT/ ENERG (Higher energy consump-tion)	Minor challenge but so far not considered	I12,I13,I15	• *"It is likely to be higher per unit for AM. But I am not sure."*(I12) • *"They probably use more energy. I know some printmakers have started developing materials that require less heat to melt. But I do not really know how much energy AM machines generally use."*(I13)
STAT/OC (Other challenges)	None		

5.3.2 Challenges within line science

Many of the interviewees with more technical knowledge see additional post-processing as one of AM's biggest challenges. Several interviewees mention support materials or powder-beds needed for building that need to be removed after production. Most of these processes are currently done manually as I12 explained, *"There is a lot of manual labor (…) It is not so plug-and-play. Elements cannot just fall out of the machine."*

The non-automated AM machines contrast the super-efficient operations LEGO is currently running with traditional manufacturing. I5 explains that *"AM is a bit like our production was back in the 60ies before injection molding was properly automated."*

Complicating AM even further is the post-process of quality control. With mass-produced parts, it is sufficient to control just a fraction of products and assume consistency. But lower volumes could increase the need for more frequent quality control. As I5 asks, *"How do we approve products? (…) We need to find a different way to do it because we still need to guarantee product safety and quality."*

High throughput time was mentioned by many interviewees as well. As I1 explained, *"We can only use the technology as a safety net if it doesn't become super expensive and slow."* However, just as quality is improving, speed seem to be improving rapidly as well. For this reason, it is not of grave concern to most interviewees. And as I13 explained, *"Print time is still a challenge (…) But it has developed. And in 5-6 years, it will likely have increased drastically."*

No other challenges within line science were found.

Table 10: Line science challenges

Code and theme	Primary finding(s)	Interviewees confirming	Exemplifying quotes
LINE/ POST (Additional post-processing)	Major challenge since the level of post-processing is high and that it does not fit into current production setups	I2,I5,I8,I12, I13,I15	• *"There are so many "secrets" with AM [after production]. Sometimes you have to remove a powder-bed. Sometimes you need to color it afterwards. Or sometimes, you have support material."*(I5) • *"One of the key advantages of AM is responsiveness. (…) But I need to scrape stuff off afterwards, it takes so much time to do."*(I8) • *"Why is there a door like a fridge? It has to be automatic. They are not ready for production"*(I12)
LINE/ THRO (High through-put time)	Challenge, but technology is improving rapidly	I1,I2,I5,I10, I12,I15	• *"If you print many items together [to increase speed], they might affect each other and decrease quality"*(I2) • *"You cannot at all compare it 1:1 with injection molding. That is not the right thing to do, because it gives flexibility in a way, you do not get from injection molding"*(I12)
LINE/OC	None		
Other challenges			

5.3.3 Challenges within network science

To the interviewees, the challenge related to fixed mindsets and lack of AM skills was one of the biggest concerns. First of all, the skills of the company are tightly linked to the traditional injection molding, and as I1 puts it, *"We have been doing things the same way for like ever. And we became really good at it."* This gives procedural bias to an organization. Some of the interviewees were even quite honest and admitted that they feared being too unfamiliar with AM to actually leverage the technology. Most interviewees focused on the technical challenges AM might pose to current engineers and designers. But I9 explained that it also stretches to the marketing function; *"Our go-to-market strategy is structured around high-volume products. (…) The KPIs are not set up for niche products. (…) AM can create value through 'innovation aura', but we don't measure on that today."* Adding to it, I7 interestingly pointed out that *"The capital investment we have made is almost a natural bias."*, meaning that the investments in molding facilities can be hard to discard even if something better comes along. This dynamic could fix mindsets even further.

During the investigation, another challenge related to fixed mindsets occurred. Part of LEGO's organizational structure is based around traditional manufacturing techniques. However, AM might require people to work together in different ways. While testing an AM technique, I12 explained that, *"We thought the use of the printer would be the biggest challenge. But the biggest was that our [job role] and our [job role] had to work together differently. And that gave a lot of problems."* (I12). Several other interviewees followed up with similar concerns which poses the question, are current organizational structures built for traditional manufacturing processes capable of truly leveraging AM technology?

Table 11: Network science challenges

Code and theme	**Primary finding(s)**	**Interviewees confirming**	**Exemplifying quotes**
NETW/ MIND (Fixed mindsets and lack of skills)	Major challenge since skills, capital and operations strategy all center around current technologies	I1,I2,I3,I4,I6, I7,I8,I9,I10, I12,I13,I14	• *"The discrepancy between future production and day-to-day, bridging that gap is a challenge."*(I2) • *"I am not sure I have enough knowledge about AM to actually use it when optimizing"*(I6) • *"There is a tendency to believe that what works now will work in the future"*(I7) • *"Someone's bread and butter is related to the current technology. It is not human nature to give it up then."*(I7) • *"LEGO has been using ABS for God knows how many years. So, we know ABS. (…) There is still a lot of uncertainty around AM."*(I8) • *"Our legacy systems can hinder the space for new technologies"*(I14)
NETW/ OC (Other challenges)	Organizational structures are often build around current manufacturing technology. Changes might be needed to take full advantage of AM.	I9,I10,I12, I13,I14	• *"We work a lot in silos. One silo boss has to talk to another silo boss. And before the second silo boss has talked to his people, it has taken a year or it has faded out beforehand."*(I9) • *"When looking at digital, there is already now a need for a more matrix structure"*(I10) • *"We already see now that AM doesn't really fit in, and that multiple departments try to build competencies without learning from each other."*(I13) • *"Maybe we should organize ourselves more in tribes that have all competencies in order to deliver the product to the consumer"*(I14)

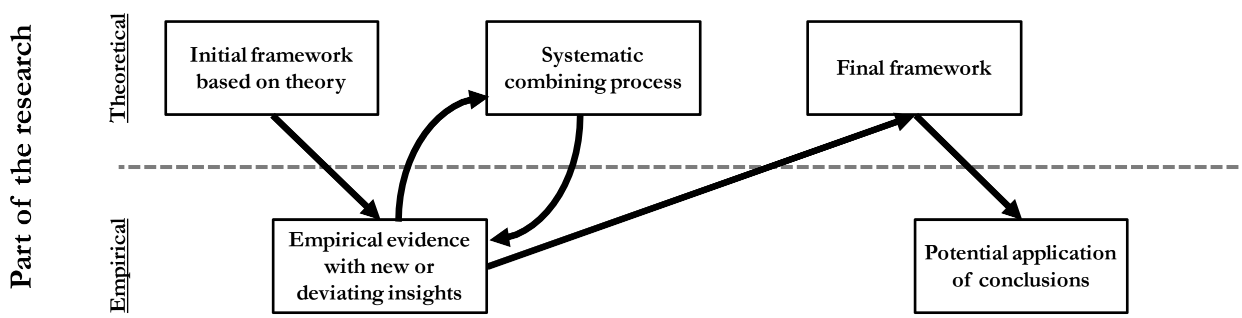
6. Discussion

In this section, the theoretical findings will be refined using the empirical data analyzed in the previous section. The section will begin by going over general reflections followed by a reconciliation of the theoretical advantages and challenges with the empirical findings. This will lead to an updated version of the management framework. Afterwards, the implications will be discussed on a more abstract level to complement the detailed findings of the framework.

6.1 Refining the theoretical findings

As an abductive study, the thesis will now lay out the refinement of the theoretical findings presented in the initial framework. Through an iterative process of systematic combining, insights from the empirical evidence will be integrated in order to refine the initial framework and ultimately arrive at a new improved final management framework (Kovács and Spens, 2005).

Figure 6: Illustration of the abductive refinement



Note: Based on Kovács and Spens (2005).

Before detailing the individual implications, the thesis will reflect on some general observations relevant to the rest of the discussion.

First, it must be asked if AM is at all relevant to a high-volume manufacturer like LEGO? All interviewees seemed to be convinced that AM had some future at LEGO. However, they were also very clear that they did not expect their current manufacturing systems to be completely replaced by AM in the foreseeable future. Instead, they believed AM would be able to complement their current setup. This also means that several of the "ideal" and hyped traits of AM are not as relevant to them currently. For instance, the idea of very localized production with reduced logistics and almost no inventory is not an issue for them since the potential parts printed need to be combined with parts from regular factories. But on the other hand, some of the biggest disadvantages are also alleviated by AM playing a complementary role in production setup. Therein lies a big difference between the mass-producers, like LEGO, and manufacturers producing unique or very low-volume items.

A second general finding was that the implications vary dramatically in importance. Some of them, higher energy consumption for example, are concerns, but only minor ones. Others such as post-processing and lack of skills are of great concern. Therefore, distinguishment between the identified benefits and challenges is needed. This will be done in the following discussion by rating the importance of each implication. A scale from +/- 1 to 3 has been chosen because it is basic enough to keep the management framework and insights simple, but granular enough to recognize that all implications are not equal.

6.1.1 Reconciling the theoretical advantages with the empirical findings

Beginning with no tooling cost, the theoretical arguments and empirical view align very well since both view it as a major advantage. Also, from a station science point of view, this advantage is the most important for a large manufacturer with extensive tooling. The potential of less tooling has significant consequences for product development and marketing restrictions. Therefore, this advantage will be rated 3+ in the framework.
Similarly, theory and empirical findings also align for greater design freedom and part consolidation. The advantages are not as significant as no tooling, but they are important when evaluating AM. AS such, they will be rated 2+ in the framework.

Theory and reality does however not align as well for most other advantages. The advantages of lower lead time, lower inventory and reduced logistics are all celebrated in prior research. For high-volume manufacturers, they can be beneficial, but their impact is significantly reduced due to AM only being seen as a complementary technology. Past research has primarily investigated these advantages in settings of low-volume production settings. Therefore, it has disregarded how connected processes across the supply chain reduces the upsides. For example when a company only produces part of a product using AM, the company will still need traditional manufacturing for the rest of the product. This reduces the potential to localize production and reduce inventory since they still rely on the inflexibility of the traditional system. In the framework, lower inventory and reduced logistics are rated 1+ since they are minor benefits. Lower lead times is seen as a slightly more significant. Given that it can be used to bridge manufacturing gaps, it has been rated 2+.

The biggest divergence between theory and empirical findings was found for the issue of waste reduction. The thesis has not been able to confirm this advantage. Prior research tends to depict current manufacturing as very wasteful and AM as the opposite. On the surface, this is easy to conclude when comparing additive to subtractive production techniques. However, this conclusion is inaccurate. Current manufacturing has managed to optimize and reduce waste over decades while AM often spoils material when changing from one material to another and wastes materials in support structures. Furthermore, many AM techniques do not have the opportunity to recycle used material. As a result, waste reduction will not be included in the framework. Reduced waste might be an advantage in other industries, especially where input/output ratios are critical, but since there is no supporting evidence in the case study, it would not be methodologically consistent to include it. Neither will the related advantage of sustainability be included in the framework. Nothing indicated during the empirical investigation that AM is more sustainable than traditional manufacturing.
The same goes for upgradability. This potential advantage was hard to investigate since LEGO's business model centers around modular products already. Upgradability could presumably be an advantage in some industries, but since no empirical evidence supports it, it has been excluded from the final framework.

In spite of not being frequently mentioned in theory, the data heavily emphasized the potential of AM in reducing time to market. The time it takes for high-volume manufacturers to respond decreases opportunities to profit on new trends. In an industry where trends are not as variable as in the toy industry, the advantage might not be as significant. However, for the high-volume consumer goods company, this has been deemed a major advantage why it will be rated +3 in the framework.

AM as a digitalization driver was sporadically supported by the empirical data. However, a pattern emerged during the investigation of many interviewees viewing AM as a way to prepare LEGO for the future, something that prior research had not emphasized. Based on the data, this was considered a major advantage. Part of this advantage is driving digitalization, but it goes further by also including the knowledge and skills of employees. This notion of development for physical and human resources will be captured by the term "modernizing supply chain." This advantage is rated 3+ since it is empowering manufacturers internally to better respond to future external challenges.

Table 12: Reconciling the advantages

Code and theme	Empirical findings	Comments on match with theory	Importance
STAT/TOOL (No tooling cost)	Major advantage	Aligned	+ + +
STAT/DES (Greater design freedom)	Advantage	Aligned	+ +
STAT/WAST (Less waste)	Not supported	Frequently mentioned in theory, but without support in data, it will not be included in the framework.	/
LINE/PART (Part consolidation)	Advantage	Aligned	+ +
LINE/TTM (Faster time to market)	Major advantage	Not too frequently mentioned in theory but seen as a major advantage in the data	+ + +
LINE/LEAD (Lower lead time)	Advantage	Praised in theory, but only a regular advantage as long as complementary. Could be major advantage in industries where spare parts are frequently needed.	+ +
NETW/INVT (Lower inventory)	Minor advantage	Praised in theory, but only a minor advantage while being a complementary technique.	+
NETW/LOGI (Reduced logistics)	Minor advantage	Praised in theory, but only a minor advantage while being a complementary technique.	+
NETW/UPGR (Upgradability)	Case not suited to investigate	Will not be included in framework due to lack of data. Could potentially be beneficially in other industries.	/
NETW/SUST (More sustainable)	Not supported	Removed from framework due to no support at all, in spite of being emphasized as great advantage by some theorists.	/
NETW/DIGI (Digitalization driver)	Not directly supported/hard to achieve saturation	Merged into advantage regarding modernization of supply chain.	/
NETW/OA (Other advantages: Prepare manufacturers for future challenges)	Major advantage	Not directly mentioned in prior research but seen as major advantage and merged together with digitalization driver to deal with overall modernization of the supply chain.	+ + +

6.1.2 Reconciling the theoretical challenges with the empirical findings

Among the challenges, low quality, high throughput time and low economies of scale are mentioned consistently in prior research as challenges to AM. However, the empirical findings tell a different story. Low quality is still a challenge, but the technology has definitely improved in terms of quality. In the framework, quality issues will be rated -2 since it is still one of the biggest obstacles to AM. But to reflect the development, the name of the challenge will be updated to "lower quality." Throughput time is also advancing rapidly, but it is even less of a concern according to data. Due to this, it will only be rated -1 in the framework.

Low economies of scale is not concerning according to the empirical findings, as long as the technology is complementary. Thus, economies of scale will not be as big an issue. Because of the lack of empirical support, this issue has been removed from the framework.

Post-processing has only been mentioned by a few theorists, but to the practitioners, it is currently a paramount challenge for the technology. To use AM for end-products, the machines must fit into a production line. Currently, AM requires a lot of manual labor for all the processes involved in production. This cannot be ignored when evaluating the technology why it has been rated -3.

Fixed mindsets and lack of skills was also not mentioned frequently as a challenge by theorists, but the data painted a different picture. From working inside in the organization, it was clear that for a company with proud traditions for a certain production technology. Even as just a complementary production technique, there are many unpronounced barriers to full acceptance of AM. The vast support from the case on this matter leads to a -3 rating in the framework.

The challenge with outdated organizational structures not considered by prior research is also a challenge worth including in the framework. Manufacturers might have organized themselves partly around the processes of traditional manufacturing, e.g. with a molding department. As AM begins to complement the traditional techniques, legacy organizational layouts may not be optimal. In spite of this concern, it is however a minor one that will be rated -1.

Shifting gears, theory and data was well aligned on a few points. Most importantly, the problem with scarce and expensive materials was confirmed by both. These issues are a major challenge to leveraging the full potential of AM. Thus, this issue is rated -3 in the framework.

For higher energy consumption, theory and data were similarly aligned, viewing the issue as minor. However, likely due to LEGO not using AM for end-products yet, the empirical data was scarce on this issue. Given the alignment on higher energy consumption, it has been rated -1 in the framework.

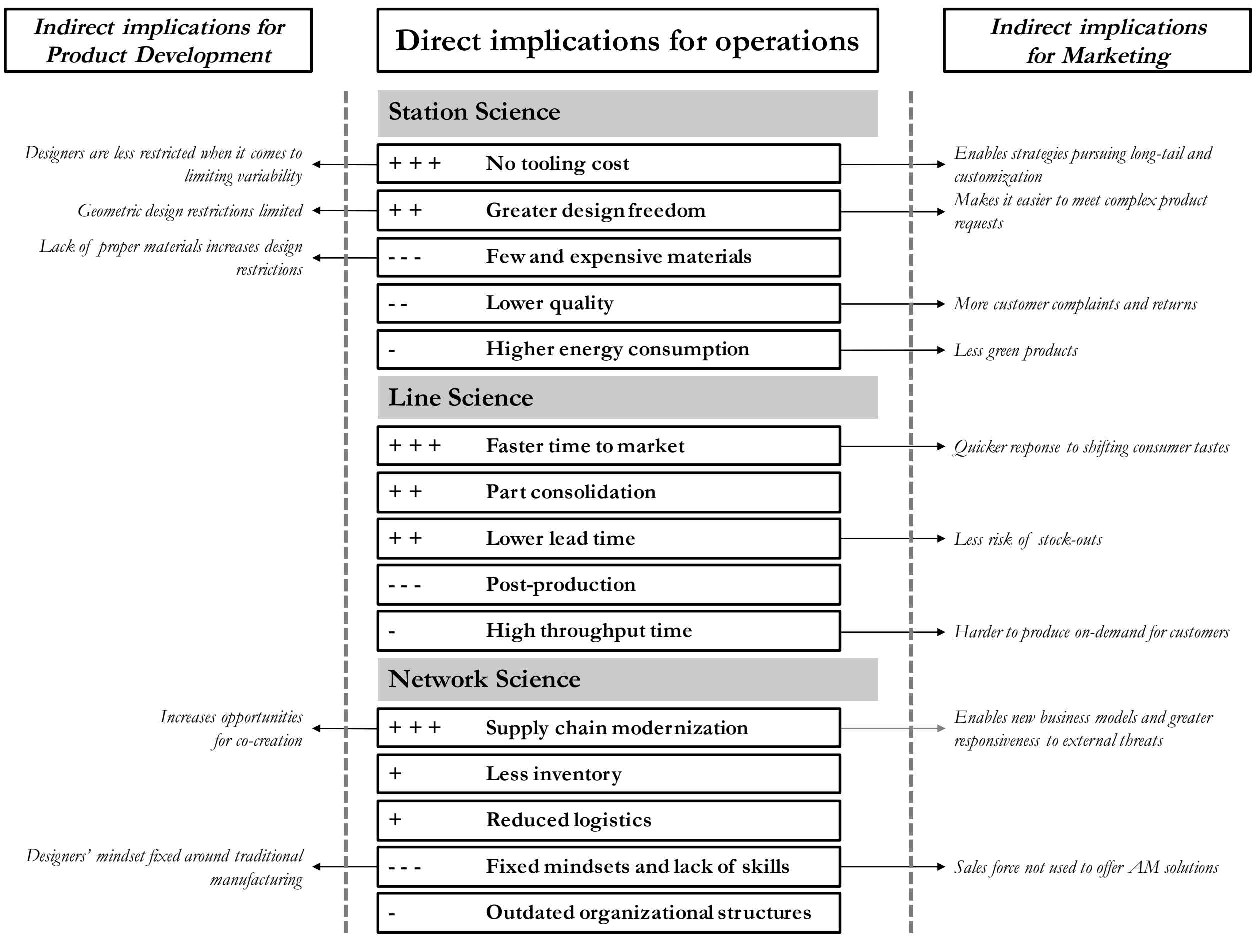
Table 13: Reconciling the challenges

Code and theme	Empirical findings	Comments on match with theory	Importance
STAT/QUAL (Low quality)	Challenge	Emphasized as a very big challenge by prior research, but in reality, a manageable one due to the technological development	- -
STAT/MAT (Few and expensive materials)	Major challenge	Alignment	- - -
STAT/EOS (Low EOS)	Not supported	Emphasized by many theorists as a big challenge, but will not be included in framework due to lack of empirical evidence.	/
STAT/ENRG (Higher energy consumption)	Minor challenge	Alignment, but lack of saturation	-
LINE/POST (Additional post-processing)	Major challenge	Often overlooked by theorists, but in empirically a major challenge since it could be the largest obstacle when it comes to integrating it into large scale production	- - -
LINE/THRO (High throughput time)	Minor challenge	Often theoretically emphasized as a big challenge, but only a minor challenge according to the empirical evidence due to technological developments	-
NETW/MIND (Fixed mindsets and lack of skills)	Major challenge	Often overlooked by theorists, but empirically a major challenge due to the large-scale operations of big manufacturers	- - -
NETW/OC (Other challenges: Outdated organizational structures)	Challenge	Not mentioned in prior research but empirically a challenge, especially for a established companies where it will be a minor technique compared to a dominating technique	-

6.2 Refined management framework for AM implications

Based on the discussion, a refined and weighed framework is presented in the figure below which summarizes the detailed answers to the research question and sub-questions outlined above. The framework can be used to evaluate the technology overall, to evaluate producing a single product using AM, or to evaluate using AM to produce a single part of a product.

Figure 7: Final management framework for evaluating potential AM implications



However, it is important to note that a technological framework like this will never be static. In 5 years, it is likely to look different. Especially the two challenges regarding quality and throughput time are already now on a clear trajectory towards improvement according to the empirical findings. It will also be interesting to follow the development of more automated processes for post-processing and the market for materials.

Furthermore, a large shift would occur if AM transitions from complementing to replacing traditional manufacturing techniques. This transition would like increase benefits such as reduced logistics and lower inventory, potential challenges such energy consumption would have to be investigated further, and the excluded challenge of low economies of scale might be relevant to include in the framework despite lacking empirical evidence.
Finally, for other industries, it may be relevant to evaluate AM's potential to reduce waste or create upgradable products. These potential advantages were excluded from the framework due to lacking empirical evidence for the case company.

6.3 Taking the implications to a more abstract level

The framework outlined is the result of a thorough investigation into AM and its implications. However, the framework is very detailed and will likely and as mentioned, need to be updated over time. Therefore, it is pertinent to discuss the findings on a more abstract level.

Throughout the research process, it became clear that multiple implications commonly affect manufacturers' ability to handle variability through buffers. Variability is defined as *"the quality of nonuniformity of a class of entities"*, or more informally, simply the degree to which a group of entities vary (Hopp and Spearman, 2001, p. 249). Variability can both be controllable (e.g. selling customized products) or random (e.g. fluctuating demand or machine breakdowns). Moreover, variability can both result from the production process (e.g. because a tool is not available) or from the product itself (e.g. because of complex geometric structures). No matter the source, variability reduces the performance of a manufacturing system by creating irregularities, bottlenecks, defective products, queues, longer lead times, etc. (Hopp and Spearman, 2001; Hopp, 2008; Simchi-Levi, 2010).

All variability will be buffered since buffers are what compensate for variability. As Hopp (2008) states, *"variability in a production or supply chain system will be buffered by some combination of inventory, capacity and time."* (Hopp, 2008, p. 80). Inventory buffers work by storing excess products or work-in-progress to mitigate the irregularities. Time buffers work by delaying the product flow through the system. Capacity buffers work by having idle capacity to compensate for the variability. However, all buffers are costly. Inventory and extra capacity increase expenses while time buffers often impair customer experience. It is important to stress that variability not just can be buffered. Variability will be buffered by some combination of creating inventory, adding extra capacity or slowing down throughput time (Hopp and Spearman, 2001; Hopp, 2008).

According to the empirical evidence, a few implications of AM could increase the need for buffers, but more could reduce the need for buffers. The reduction could happen through two mechanisms. First, AM could reduce the use of buffers by, for example, reducing time consuming steps of the production process or by needing less inventory on-hand. Second, AM could make the capacity buffer (and potentially also the inventory buffer) more flexible, meaning it would be easier to handle product variability with the same machine capacity. Both mechanisms lead to a reduced need for buffers.
The table below gives an overview of how the relevant implications could affect the buffers of a manufacturing firm.

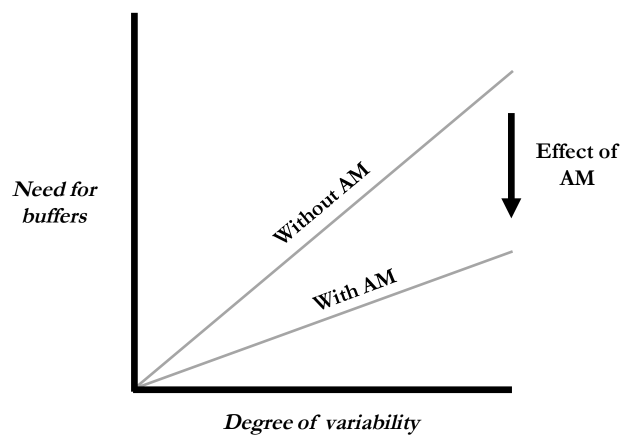
Table 14: Implications affecting buffers

Implication	Inventory buffer	Time buffer	Capacity buffer	Explanation
No tooling cost		Decreased need	Improved flexibility	Multiple-purpose machines makes capacity more flexible requiring less buffer to handle variability from the number of products. No tooling reduces the time before production can start.
Greater design freedom	Improved flexibility		Improved flexibility	AM machines are more flexible when producing convoluted structures requiring less buffer to handle variability from geometric complexity Raw material could be used for multiple components making inventory more flexible.
Faster time to market		Decreased need		Less time is needed to launch new products.
Part consolidation	Decreased need	Decreased need		Less work-in-progress and less production steps due to part-consolidation reduces the need for inventory buffer. Production of product is faster due to fewer steps reducing need for time buffer.
Lower lead time	Decreased need	Decreased need		Less time is needed to deliver existing products. Inventory can (to some degree) be raw material instead of finished products.

Less inventory	Decreased need		Less need for inventory buffer.
Additional post-processing		Increased need	More time is needed due to slow post-processing.
High throughput time		Increased need	More time is needed for the production itself.

AM could decrease the need for buffers if the manufacturer can manage the negative implications of time buffers, especially in post-processing. Taking the aggregate level of analysis into account, the following figure illustrates that with AM, less buffer will be needed to handle the same amount of variability.

Figure 8: Decreased need for buffers



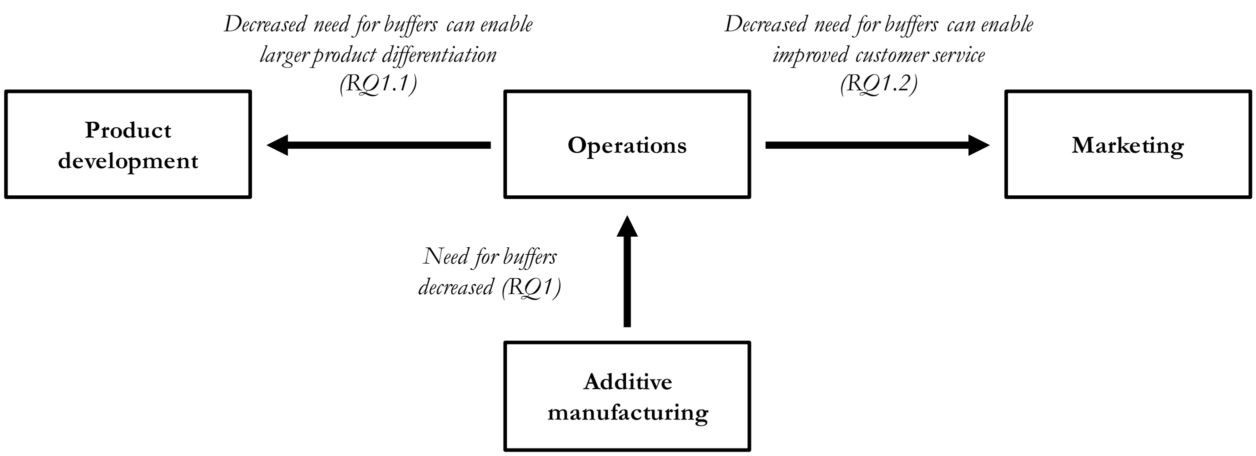
Going back to the main research question, the direct implication of AM can be reformulated as a decreased need for buffers. But what might the indirect implications of the decreased need for buffers be?

According to the empirical investigation, product development could indirectly benefit from reduced need for buffers. Currently, product development aims to reduce the general number of parts and SKUs in order to limit variability in the supply chain. With AM, these restrictions could be loosened since product differentiation and hence variability will not require the same buffer level required of a traditional manufacturing system. In other words, developers could be more creative and produce more differentiated or complex products without incurring the high costs as they would in traditional manufacturing.

Furthermore, the reduced need for buffers could also indirectly benefit marketing. The empirical data supported how increasing customer service by responding to new trends and delivering orders quickly is costly since it leads to higher variability and thus increases the need for buffers. With AM, because the variability incurred will not require as big buffers, it could become easier to respond quickly and manage smaller batches of products with shorter life-cycles.

Let's sum up by going back to the research question and sub-questions. In a more abstract fashion, the following figure answers the question of what the potential of AM can be if the outlined potential downsides are mitigated.

Figure 9: Abstract implications of AM



7. Conclusion

This section will briefly summarize the key findings of the thesis in the context of the research question and sub-questions. Then, the theoretical contributions and managerial implications will be presented. Finally, the limitations of the thesis will be outlined followed by suggestions for future research.

The study was initiated based on the gap between the managerial potential and the managerial knowledge of AM. The aim has been to bridge part of this gap by investigating the internal consequences of AM for manufacturing firms. More specifically, the thesis has tried to build a more holistic understanding than prior research with a focus on high-volume manufacturers which, despite being the dominant type of manufacturer, have been largely ignored by past researchers.

Through the initial literature review and subsequent refinement via the empirical study, 8 advantages have been identified. The three most important ones are detailed in the following: 1) AM operates without the high tooling costs of traditional manufacturing. This can make it more feasible to target smaller customer segments, while also lowering restrictions during product development. 2) AM can improve time to market for manufacturing firms. Tooling often contributes to manufacturers' the low responsiveness, which can make it harder to respond to shifting trends. 3) AM can be a driver for supply chain modernization of manufacturing firms. Most importantly, the modernization can empower manufacturers to better manage future challenges.
Also, 7 challenges have been identified. The three most important ones are detailed in the following: 1) There is little competition and variety in the supply of materials. This leads to anticompetitive production costs and design restrictions due to limited materials with the right properties. 2) Post-processing of AM products is intensive and requires expensive manual labor. 3) Manufacturers and their employees might have fixed mindsets against this new technology and lack the skills to fully capture the potential benefits.

On top of the 15 outlined implications, the thesis has also found that many of the implications affect company buffers. Most of them are positive, especially if the post-processing and the throughput time challenges can be mitigated. Going back to the main research question (RQ1), this means that AM has the overall potential of decreasing the need for buffers. This decreased need is a result of improved and more flexible processes that diminish the amount of capacity required to mitigate variability. This is a direct benefit to the operations, but if we look at the indirect implications (and the sub-research questions), this also holds great potential. For product development (RQ1.1), the need to control variability when developing new products is decreased since the variability from an increased number of SKUs, for example, will not require as big buffers. For marketing (RQ1.2), the more flexible production can lead to the pursuit of new business models, for example by targeting smaller customer segments.

7.1 Theoretical contributions

The AM research agenda is in its infancy, but as argued previously, coherence of arguments and concepts has begun to materialize in prior research. The first contribution of the thesis is the review of prior research and the synthesis of those arguments into an initial framework. This can enable scholars to quickly get an overview which has not previously existed.

Second, the thesis contributes by creating and refining a framework for AM implications (the most holistic management framework to date, to the best of the author's knowledge). Through the empirical investigation, implications are assessed and weighed, and other potential implications are explored. This investigation has increased understanding of the nature and magnitude of the individual implications, and led to critical remarks on some of the implications, especially in regard to claims of AM being a very sustainable production method. Furthermore, it has led to new implications being incorporated that previous research has focused less on.

Third, the thesis conceptualizes how AM affect buffers. As such, the insights of the thesis are more robust towards technological developments. Furthermore, the thesis links the AM agenda to developed fields within operations science such as capacity and inventory planning, making AM relevant in a broader context.

Finally, the thesis analyzes high-volume manufacturers as opposed to most prior research which focuses primarily on low-volume processes. As argued previously, most items are mass-produced and so it is relevant to develop insights specific to high-volume manufacturing firms.

7.2 Managerial implications

All manufacturing managers are probably aware of AM and its hype as a game changing future technology. However, when the author began reviewing literature on AM, it was surprising how hard it was to get an overview of its potential implications. With the presented management framework, the hope is that this will be easier in the future. The framework is meant as a tool for manufacturers to initially assess the implications of using AM and can be useful both when considering producing an entire product or only a part of it using AM.

Furthermore, the buffering insights could help companies on a more abstract level understand the implications of AM, how it alters internal trade-offs and what products/parts might make AM a good complementor to traditional manufacturing. These insights are linked to the more generic construct of variability and buffers used in disciplines across supply chain management making it easier for companies to relate them to their current practices (Hopp, 2008).

7.3 Limitations

Being a qualitative, single-case study leads to the primary limitations of the study. It is by nature difficult to establish inference based on a low sample size. Being a single case study, the sample size of one makes it even harder. For LEGO in particular, the company operates in a very specific industry that might not be comparable to other industries. Furthermore, LEGO primarily produces plastic items which is just one of the materials where AM could be relevant, and it has not yet produced end-products using AM.

As such, the thesis cannot claim that the exact findings of the study are applicable for all other high-volume manufacturers. They should be used critically. However, the aim of the thesis has never been to claim external validity but to build and refine theory.

Furthermore, the more abstract findings related to buffering are not as well developed throughout the thesis as the detailed implications of AM. This is due to the exploratory nature of the study and the time restrictions of a master thesis. During the successive refinement process, it occurred how many of the implications held the denominator of affecting buffers. This insight was too valuable to exclude from the thesis, but had it been known from the beginning, it could have been developed more thoroughly.

7.4 Future research

In spite of contributing a holistic management framework of AM implications, more research into AM is still necessary, especially due to the single-case methodology applied in the thesis. Exploratory studies are needed to investigate implications across different firms, industries and materials and to make sure constructs outlined in this thesis and prior research are relevant. When a level of saturation has been achieved, it would be relevant to test some of the constructs using a more deductive approach in order to increase the external validity and strengthen the results.

As described, AM could potentially decrease the need for buffers. Future research might dig deeper into the potential consequences for buffers. Many managerial concepts and theories (e.g. capacity planning, inventory management and lean) are built around the assumption that production systems are inflexible and that variability is problematic (Hopp, 2008; Modig et al., 2017). Will AM change this profoundly? If so, what will the consequences on our managerial practices be?

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9. Appendix

9.1 Overview of interviews

#	Date	Interviewee ID	Position	Type of interview	Way of conducting	Duration	Comments
1	16-Feb	I0	Senior manager, operations	Open-ended	Skype	01:05	Pre-study
2	27-Feb	I1	Senior director, value chain	Semi-structured	Skype	01:00	
3	1-Mar	I2	Designer/engineer	Semi-structured	Face-to-Face	00:55	
4	6-Mar	I3	Director, supply chain	Semi-structured	Face-to-Face	00:55	
5	8-Mar	I4	Director, value chain	Semi-structured	Skype	00:45	
6	15-Mar	I5	Manager, materials	Semi-structured	Face-to-Face	00:55	
7	16-Mar	I6	Director, marketing and TTM	Semi-structured	Skype	00:30	Interview interrupted
8	19-Mar	I7	Director marketing	Semi-structured	Skype	00:50	
9	3-Apr	I8	Designer	Semi-structured	Face-to-Face	01:00	
10	3-Apr	I9	Director, executive team	Semi-structured	Face-to-Face	01:00	
11	3-Apr	I10	Director, AM team	Partly open-ended	Face-to-Face	01:00	Interview used to present priliminary findings
12	3-Apr	I11	Senior manager, product development	Semi-structured	Face-to-Face	00:55	
13	4-Apr	I12	Manager, prototypes	Semi-structured	Face-to-Face	01:05	
14	4-Apr	I13	Engineer	Semi-structured	Face-to-Face	01:05	
15	5-Apr	I14	Senior manager, planning	Semi-structured	Face-to-Face	01:05	
16	17-Apr	I15	Senior engineer, AM team	Partly open-ended	Face-to-Face	01:10	Interview used to present priliminary findings
17	24-Apr	I10	Director, AM team	Partly open-ended	Face-to-Face	01:00	Interview used to present final findings

9.2 Overview of observations

#	Date	Type	Of what?	With whom?	Way of conducting
1	21-Feb	Observation	Workshop	20 employees from different parts of the company	Participation
2	22-Feb	Observation	Factory visit, molding facility	Director, AM team	Live observation
3	28-Feb	Observation	Visit to test center	Senior engineer, AM team	Live observation
4	20-Mar	Observation	Visit to prototyping facility	Manager, prototypes	Live observation
5	23-Mar	Observation	Coordination meeting on AM	6 employees from different parts of the company	Live observation

9.3 Days spent at LEGO's HQ

#	Date
1	11-Jan
2	6-Feb
3	19-Feb
4	21-Feb
5	22-Feb
6	28-Feb
7	1-Mar
8	6-Mar
9	7-Mar
10	15-Mar
11	16-Mar
12	19-Mar
13	20-Mar
14	22-Mar
15	23-Mar
16	3-Apr
17	4-Apr
18	5-Apr
19	17-Apr
20	23-Apr
21	24-Apr
22	3-May
23	4-May
24	7-May

9.4 Interview guide used for semi-structured interviews

Briefing:

- Presentation of project and author
- Explanation of procedure
- Permission to record
- Questions about title

Introductory questions:

- Could you explain what you do in your current position in LEGO?
    - Have you worked in any past positions in the firm as well?
- Tell me about your current work
- What challenges are you dealing with right now?

Initial thoughts on AM:

- What is your first thought when I mention additive manufacturing/3D printing?

    - Are you working with it already?
- Where do you see the biggest advantages of AM?
- Where do you see the biggest disadvantages?

Questions on product development, operations and marketing:

- LEGO can be said to be divided into three parts: Product development, operations and marketing:
    - Can you see AM affecting the development of new products (beyond prototyping)?
    - How about the operations part regarding manufacturing, logistics and so on?
    - And finally, what about the marketing part? Do you see any potential influence of AM on this part?

Potential areas to ask about / follow-ups if not touched upon already (based on the literature review):

<u>Potential advantages:</u>

- No tooling cost
- Greater design freedom
- Part consolidation
- Waste reduction
- Faster time to market
- Lower lead time and less inventory
- Reduced logistics
- Upgradability
- More sustainable
- Crowd-sourced design
- Digitalisation driver

<u>Potential challenges:</u>

- Lower quality
- Restricted variety of materials

- No economies of scale
- Low speed
- Post-production
- Higher energy consumption
- Lack of skills and fixed mindsets

Conclusion:

- Are there any points I haven't had answered yet?
- Would it be okay if I got back to you at a later stage if I had any remaining questions?