ENHANCING THE TECHNICAL RESILIENCE OF CRITICAL INFRASTRUCTURE WITH ADDITIVE MANUFACTURING

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ABSTRACT

Purpose

The purpose of this study was to explore the potential of additive manufacturing (AM) for improving the logistics of supplying critical spare parts, so that larger quantities of spare parts can be manufactured directly in the field. A contribution of the study is to address the need to reduce the storage of spare parts, shorten repair time, increase the usability of resources, test the concept of operation, enhance the readiness time of the critical infrastructure, and heighten its technical resilience.

Design/methodology/approach

In this study, we investigated the internal resilience of waterworks, particularly “technical resilience,” which here is interpreted according to the approach and definitions of the US National Infrastructure Advisory Council. The Hayes and Wheelwright four-stage model of operations strategy (1984) (Hayes & Wheelwright, 1984) was applied to the present case, which focused on the spare parts supply chain, production, and operational needs. The perspective of the study was a worst-case scenario in respect of critical parts of the water pumps of the waterworks, which were computer-aided design (CAD)-modeled and additive manufacturing (AM) simulated.

Findings

In the present case, it was found that four fifths of the critical spare parts could be 3D-printed directly and one fifth could be cast. This suggests that 3D printing can increase the availability of spare parts, especially in a situation where the security of supply has declined.

Research limitations/implications

This study was limited to the operational environment of one Finnish waterworks and one of its pump types, in a setting in Finland where 3D printers were available.

Original/value

Technical resilience and AM were examined and evaluated in this study mainly from the point of view of supply chain resilience and AM in the spare parts supply chain in the context of a critical infrastructure. The results may be valuable to decision-makers, manufacturers, and infrastructure managers of the security of supply.

Keywords: technical resilience, additive manufacturing, robustness, supply chain, security of supply, resilience engineering

1. INTRODUCTION

In order to exist and thrive, society requires the adequate functioning of critical infrastructure (Valtioneuvosto, 2017). In this everyday operational environment, the focus is on identifying individual critical assets of the infrastructure, to safeguard their operations, and to ensure their maximum ability to perform, recover, and adapt (Kuntaliitto & Pekki, 2015). For national security, the basic needs of citizens, particularly food and water, must be satisfied. Proper water supply and water quality control ensure the availability of clean water, adequate sanitation, and wastewater treatment, for health and environmental protection (Valtioneuvosto, 2010).

The owners and leaseholders of the land on which water supply facilities are located are responsible for the protection of the water supply and for identifying risks to the supply, notably, as the Association of Local and Regional Authorities in Finland has found, operational risks in the infrastructure (Valtioneuvosto, 2017). The most effective way to reduce the risks is proper preparedness (Kuntaliitto & Pekki, 2015), which here is taken to mean the duplication of key technical equipment (Pekki, 2016). The social security strategy has identified that the unavailability of maintenance services and of critical spare parts are the biggest risks to the water supply (Valtioneuvosto, 2010). These risks are increasing as a result of the aging of the facilities and the lack of timely renewal of waterworks production equipment (Valtioneuvosto, 2010).

In this study we have researched enhancing waterworks water pumps corrective maintenance (Moubrey, 1999) with additive manufacturing. Spare parts can be manufactured for technical purposes by additive manufacturing (Khajavi et al., 2014). Due the technical development of additive manufacturing technologies, materials and methods, the potential to use it in the technical sites has increased (Berman, 2012).

The high prevalence of outsourcing of products and the lengthening of supply chains for the sake of cost-effectiveness enhance these risks (Valtioneuvosto, 2017). Because of the concentration of core competencies, some of the processes relevant to the business operations are transferred through subcontracting and outsourcing (Seuring, 2008). The main external service providers of the water supply plant include automation systems suppliers, power grid, telecommunication services, other water supply plants associated with the same network, wholesaler or processor, and critical spare parts suppliers (Huoltovarmuuskeskus, 2016).

In the case of emergency preparedness, it is important to identify the specific features that affect the availability of technical products for critical infrastructure. Operators whose supply chains need to be activated only in the event of a disturbance should invest in supply chain readiness. Such operators are forced to tolerate greater uncertainty of their normal and commercial activities in their duties and timing (Listou, 2015).

It is recognized here that supply chain activation, especially in high-risk situations, is challenging (Brusset & Teller, 2017). This means that products with a long supply chain may not be available quickly enough. Therefore, decentralizing manufacturing so that it takes place closer to the user can reduce the supply chain risks.

The pursuit of resilience can modify supply chain structures. In the future, it may be sensible to break down supply chains so as to fragment the uncertainty and diversify the risk (Malik et al., 2011). Supply chains may also be rationalized by the adoption of new manufacturing methods. In the present case, the manufacturing method examined is additive manufacturing (AM).

In AM, the parts are 3D printed in accordance with a three-dimensional model (Gibson et al., 2014). However, AM may also make it possible to create individual parts more cost-effectively than with conventional processes (Tuomi, 2003; Berman, 2012). Producing parts on demand allows a wide range of variances and timely deliveries (Berman, 2012).

AM can change the manufacturing of the products (Khajavi et al., 2014). Research is made to address how additive manufacturing can improve usability and availability of critical infrastructure cost-effectively. That may increase security of supply and the functioning of society (Valtioneuvosto, 2017).

Nevertheless, as regards the critical infrastructure, there has as yet been no research that demonstrates how AM can enhance technical resilience. Moreover, there have been no studies on how the adoption of AM in the supply chain can increase the technical recovery capacity of the infrastructure critical target. By analyzing how the adoption of AM technology in the production of critical spare parts impacts supply chain business processes and management (Khajavi et al., 2014), this paper aims to fill these gaps in research.

This study aims to fill a research gap by studying one specific part of the critical infrastructure, namely waterworks. The literature review shows that AM has developed rapidly. Research into AM and its various applications has increased, yielding much information on the usability of the method for the production of spare parts and on identifying those spare parts to which the method is suited (Khajavi et al., 2014; Reijonen, 2017). AM has the potential to become an element in the technical maintenance of systems (Moubrey, 1999). Research has investigated and evaluated the production of spare parts by 3D printer near the end user. With regard to waterworks maintenance (Huoltovarmuuskeskus, 2016; Kuntaliitto & Pekki, 2015), the identification of critical technical objects and parts and ensuring their continuous function in all situations is essential (Valtioneuvosto, 2017). Various studies have demonstrated the potential of AM methods as part of the spare parts supply chain (Khajavi et al., 2014).

In this study we selected one average Finnish waterworks, Hyvinkää, as a research object. The main technical elements of the waterworks, water pumps, were selected for this study, because their failure presents the greatest technical barrier to an uninterrupted and sufficient water supply (Pekki, 2016). The structures and elements of waterworks are globally very similar, but the technical details vary widely. In this study, we categorized water pumps spare parts (Sulzer Pumps, 2009). Critical spare parts were CAD- modelled. Productivity for all listed (FIRPA, 2017) metal AM machines in Finland was researched. Technical resilience (Carlson et al., 2012) was divided into time and features domains. The production of critical spare parts was analyzed according to the features of the technical resilience (Carlson et al., 2012).

This study is unique because the perspective of additive manufacturing applications in the critical infrastructure disturbance recovery is novel. This study addresses the idea that preparing for interrupted situations needs a new way of thinking in addition to the old one.

This study is a part of the #WINLand strategic research project, which recognizes energy, water, and food systems as a critical national infrastructure (WinLAND, 2016).The study attempts to answer the overall research questions in the #WINLand resilience and learning theme. To these overall questions, we add more specific ones. How can AM enhance the technical resilience of the critical infrastructure? How can the introduction of AM as part of the critical spare parts supply chain change the technical resilience of a critical target? How can AM production change the maintenance of critical infrastructure sites and thereby provide security of supply?

The purpose of the study is to find new information on how to develop the resilience of technical objects in critical infrastructure by improving their maintenance. Improvement in maintenance is evaluated based on the change that AM can provide (Khajavi et al., 2014). General systems theory (Bertanlaffy, 1969) serves as the theoretical basis for our analysis. The system that is reviewed is the waterworks maintenance system and critical spare parts supply chain, as well as its inherent business processes and management components.

2. LITERATURE REVIEW

This section presents our findings from the literature on AM, technical resilience, and maintenance, as well as the implications of AM for supply chain management (SCM) and technical resilience. The literature review was aimed particularly at identifying gaps in current research.

2.1. Additive manufacturing

The revolutionary prognosis of AM is based on a projection of its potential to be used in ways that have not previously been possible (Walker, 2017). AM manufactures single parts from raw material at a low price, creating and delivering a usable product. The numerical definition of the 3D printed parts either by computer or by imaging opens up the production possibilities of AM (Berman, 2012).

AM is defined in accordance with ISO/ASTM 52900 as a "process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies" (ISO/ASTM, 2016). Additive manufacturing, 3D printing, rapid prototyping (RP), or rapid prototyping and manufacturing (RP&M) are "common denominators for a group of manufacturing techniques where the physical copy is made directly into numerical definition (3D-CAD) in a fast, fully automatic, geometric-free process" (Tuomi, 2003).

The essential steps of the AM process include CAD modeling, model conversion to printable format, slicing a model for two-dimensional printing, 3D printing, and post-processing. The print is made layer by layer, hardening each layer before the next addition. Curing is done by a different method, depending on the printing technique (Gibson et al., 2014). It takes hours or at most a few days to produce prints, depending on the form, method of production, and characteristics of the part (Khajavi et al., 2014).

The main materials for AM are plastics, metals, ceramics, and composites. The materials can be manufactured either in a single-stage or a multi-stage process. In a one-step process, the shape and material properties of a piece are formed in the same process. The shape and characteristics of the product need not be processed. In a multi-stage process, the product is manufactured so that its essential shape is formed in the first step and, in subsequent steps, the material properties of the article are formed by a different method. In the case of both process methods, the production of a piece requires post-processing (ISO/ASTM, 2016). This study deals with the manufacture of metals by AM.

Compared with other methods of rapid manufacturing, such as subtractive manufacturing, AM can bring significant benefits, the most important of which are the improved use of resources in the manufacturing process and the functional integration of the manufactured parts (Barz et al., 2016).

The products manufactured by the AM process have limitations caused by the manufacturing method. The most prominent constraints on using AM have been the abundance of mass production, the variety of materials, and the size limitations of the printed products (Frazier, 2014).

Despite the limitations of the AM method, its benefits are greater than its disadvantages when used in the right circumstances. Consequently, this manufacturing method has often been chosen, as companies have identified more and more possibilities in AM. Boeing uses approximately 300 3D printed parts in its production, and General Electrics, which has explored AM since the 1990s, uses AM, and researches and develops production modes and equipment specifically for it (Catalano, 2015).

AM makes it possible to localize production, i.e., manufacture products locally, close to the customer. By the same token, production can also be centralized, if it is useful for the supply chain (Khajavi et al., 2014).

2.2. Technical resilience

Originally, the concept of resilience was used in psychology to describe an individual's ability to survive difficult circumstances or traumatic events. Generally, the concept can be understood as a dynamic process that allows the subject to adapt or recover from significant adversity. The precondition for this concept is (1) the exposure of the subject to a significant threat or damage and (2) the adaptation of the subject. (Luthar et al., 2000).

Other ways of looking at resilience are to consider the resilience both before and after the exposure to injury or only at post-injury-related activities (Carlson et al., 2012).

The National Infrastructure Advisory Council of the United States (NIAC) has defined infrastructure resilience as “the ability to reduce the magnitude, impact, or duration of a disruption. Resilience is the ability to absorb, adapt, and/or quickly recover from a potentially disruptive event" (NIAC, 2009). This definition serves as the basis for the present research, which investigates action after a failure, damage, or injury.

The overall concept of resilience can be divided into different dimensions. In the case of an industrial accident, resilience may be separated into internal and external dimensions. The internal dimension can be separated further into technical resilience, organizational resilience, and economic resilience. The external dimension can be divided into technical, organizational, economic, and social resilience. Internal resilience in this case refers to the resilience of an object owner and external resilience to an external actor, such as a community or a state (Bologna et al., 2011).

In this study, we focus on “technical resilience” within the category of internal resilience. Technical resilience refers to the ability of an organization's physical system to function after a crisis (Bologna et al., 2011).

Common features can be identified and classified for all dimensions of resilience, of which two are time and effectiveness. The time classification is divided into: preparation, mitigation, response, and recovery (Carlson et al. 2012). These categories transcend all the dimensions of external and internal resilience. The classification according to the characteristics of effectiveness is composed of: robustness, resourcefulness, and rapid recovery (NIAC, 2009).

In this study, we consider whether AM can alter the resilience of an object in terms of both time and effectiveness.

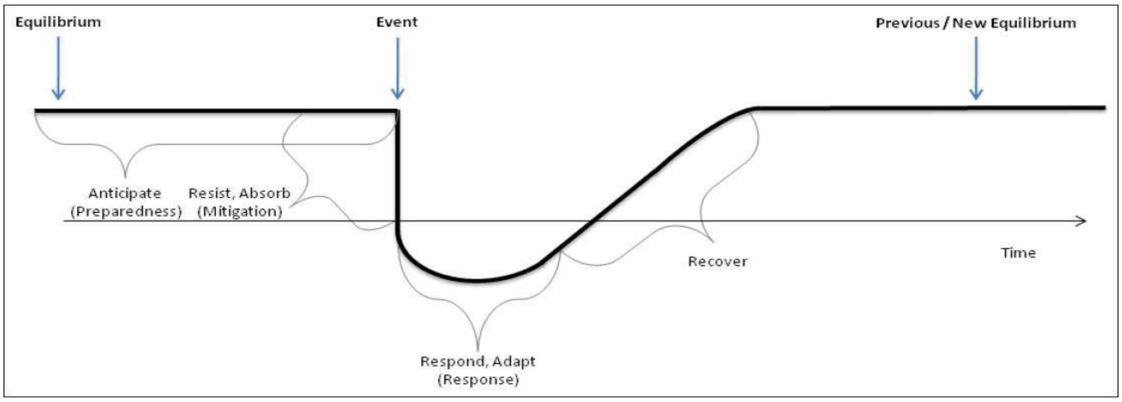

Figure 2.1 Time classification of resilience (Carlson et al., 2012).

2.3. Waterworks maintenance

Waterworks use water pumps for the transfer of water between different basins and to the network. If the water pumps at one of the plant's pumping stations fail, water distribution is interrupted (Tampereenvesi, 2017).

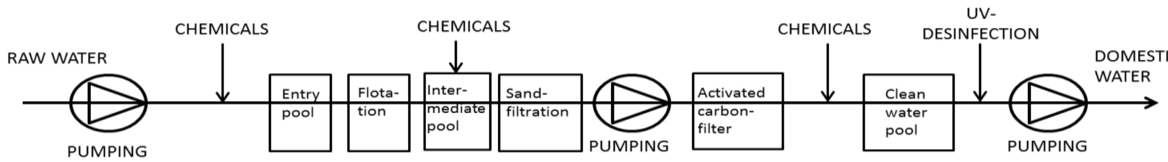

Figure 2.2 Functional diagram of the waterworks (Tampereenvesi, 2017).

There are three types of pumps in water plants: positive displacement pumps, centrifugal pumps, and submersible pumps (Minnesota Rural Water Association, 2009). Centrifugal pumps are used to pump the finished water into a network. The operating principle of the centrifugal pump is that the electric motor rotates the impeller, converting rotary energy to the liquid as a static and dynamic pressure (Jaakkola, 2012). Positive displacement pumps are used by water plants to transfer limewater to the mixing pool (Isomäki et al., 2008).

Standard SFS-EN 13306 defines maintenance as the "combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function." In this study, we focus on the applicability of AM explicitly in the technical actions, more specifically as a part of corrective maintenance (SFS-EN13306:en, 2012).

Corrective maintenance encompasses all the tasks required to restore the construction back to a state in which it can perform a required function. The fault in a construction can present itself either suddenly or over a period of time. The need for corrective maintenance can be reduced by various means, one of which is proper planning and implementation of a maintenance strategy. An example of this is reliability-centered maintenance (RMC). John Moubroy defines RMC as "a process used to determine what must be done to ensure that any physical asset continues to do whatever its users want it to do in its present operating context." AM, if applicable, can bring new design and planning elements for the entire maintenance strategy and life cycle management (Moubrey, 1999).

This study considers only the corrective maintenance aspect, not the root cause for failure. For example, technical failure can result in addition to normal wear and tear also from malicious action such as cyber-attack on the control systems of the water pumps. In the context of this study this cause is irrelevant with respect to the applicability of AM. There are many risks associated with the failure of water pumps other than those due to normal wear and tear of the mechanical device. Following a cyber-attack on the water management control system, pumps have in some instances been controlled externally to the waterworks in such a way as to cause the pumps to break (Ahlers, 2011). This particular type of failure is not investigated in the present study because this type of connection does not exist in our case.

2.4. Supply chain management with additive manufacturing

The supply chain can be defined as a multifaceted cooperation within the framework of key resources and constraints. The supply chain consists of a set of several players logically and logistically connecting to the customers of a company and its distribution and supplier network. The supply chain may comprise manufacturers of different products, their separate or collective storage, distribution centers, and suppliers to the customer. There are five recognized key factors or "flows" in the supply chain, namely information, production, service, economy, and information (Bowersox et al., 2013). Time, reliability, and transparency are the vital factors in the supply chain for the customer with respect to delivery (Logistiikan Maailma, 2017).

The production of waterworks critical technical components can be roughly divided into process production and chapter production. These can be further divided into production types. Types of production can be classed according to product variance and production volume. The production volume in turn can be divided into four parts: project production, individual production, batch production, and recurring production (Hayes & Wheelwright, 1984). AM as a method and at present capabilities naturally fits into the high variance low volume class of manufacturing.

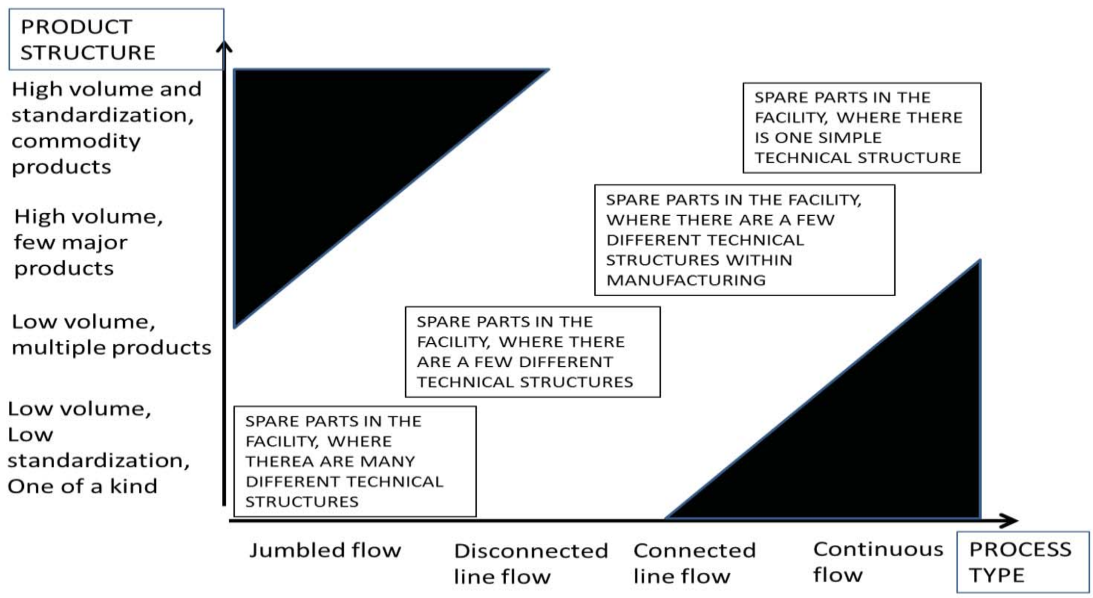

Figure 2.3 Spare parts production of critical infrastructure target from the maintenance point of view (Hayes & Wheelwright, 1984).

Production can be controlled as needed, generally by either push control or pull control. Pull control, another natural fit for AM, is a chain where customer demands are steering inventories and work in process (WIP). Products are manufactured and moved forward only if there is a need. Therefore, products should be manufactured extremely quickly in small batches as needed. (Logistiikan Maailma, 2017)

A study by Brusset and Teller (2017) investigated production control for low-volume production with a view to developing supply chain resilience, and found that that flexibility and integration are crucial to the development of resilience. Production by AM is based on the individual manufacturing of products. Products can be duplicated for printing, up to several dozen at one time, depending on the characteristics of the equipment that is being manufactured. Appropriate parts for the print products should be identified by the source of the spare parts (Gibson et al., 2014).

Increasing digitization of production may well usher in a new industrial revolution. Automating the different phases will reduce the work done by humans. The number of products that depend on human intervention will decrease with the development of AM. Products will still be capable of being manufactured individually, but more cost-effectively. The environmental friendliness of the materials will increase, as material-enhancing fabrication can minimize material loss (The Economist, 2012).

Supply chains are not as unambiguous as they once were. Modern products are often made of several parts manufactured by different manufacturers. Raw material suppliers can number in the tens, if not the hundreds, and there are several shipping companies, corporate customers, retailers, and private consumers.

AM has the potential to bring production closer to the end customer and thus reduce the constraints of traditional production chains. AM can efficiently produce small quantities of products from a large range. Production does not require major changes in production factors such as the production grid or material delivery. This allows the production of spare parts directly on the site where they are needed (Berman, 2012).

The projected classification of products for 3D printing or for conventional manufacturing should be taken into account when AM is to be used. This can be done manually or by software (Reijonen, 2017). When looking at how products can be manufactured with a variety of 3D printers, the requirements, manufacturing material, and the constraints of the printers must be considered.

We need to know the internal and external requirements of a 3D printed object in its planned operating environment. In critical situations, an evaluation can be used to determine what features can be permanently or temporarily given up or weakened to use the device.

3. METHODOLOGY

3.1. Study design and conceptual framework

The methodology of research is scenario modeling in a deductive case study. The scenario model investigates the use of additive manufacturing to produce functional spare parts for waterworks water pump. The starting premise is that the evolution of AM technology will enable a switch to the distributed production of spare parts. To be determined are the critical requirements on the development of technology to enable the change.

The case study approach was used for this study. Reference was made to “building theories from case study research” (Eisenhardt, 1989); “qualitative data analysis” (Miles & Huberman, 1994); “real world research” (Robson, 2001); and “case study research design and methods” (Yin, 2009).

The conceptual framework for the study was derived from the threat defined by the Finnish Emergency Supply Agency: “[a] situation whereby the ability to produce or acquire goods and services has temporarily been hampered” (National Emergency Supply Agency, 2017).

This kind of threat can seriously endanger the functionality of the critical infrastructure (National Emergency Supply Agency, 2017).

As our research question focused on the resilience of the critical target, we utilized end user level analysis (Robson, 2001) to evaluate technical resilience in the target (Eisenhardt, 1989) and then attempted to prove that AM can produce spare parts for the critical infrastructure's essential spare parts.

We categorized technical resilience by time and characteristics (Miles & Huberman, 1994). Time, the key dimension of this research, is examined from the availability point of view. The characteristics are common to all technical structures, giving us the opportunity to evaluate resilience (Yin, 2009). The proof of concept about AM production was made by AM simulation (Robson, 2001).

To discover whether AM be utilized to produce the selected critical parts, we digitized them using CAD modelling. Critical spare parts were identified and sorted and CAD models were made by pump manufacturer notification. All Finnish metal AM machines were explored and their building plates were simulated. Building volume and speed were investigated and spare parts manufacturing was analyzed. The printing speed and features of these machines were applied according to the specifications in the technical documents that accompanied them. After producing 3D-printed spare parts, we assessed how the supply chain would change if the spare parts were manufactured on site using AM.

3.2. Case selection

The study formed part of the #WINLand project, specifically the case of the Hyvinkää waterworks. We considered its critical objects, pumps, which form the main body of the waterworks' technical structure. Forty-eight pumps were included in the study. These pumps are based on four different operating principles. The Hyvinkää waterworks produces water for about 50,000 residents (Hyvinkään vesi, 2016).

The Hyvinkää waterworks was selected for this study, as it represents a typical Finnish waterworks. There are about 1,500 waterworks in Finland, of which about half are municipal. In addition, the single type of pump chosen for 3D-modeling is very common in Finland and therefore represents common waterworks techniques and mechanisms, from which generalizations and proof of concept for AM applicability in corrective maintenance may be made.

The case was selected because it is an excellent example of one of the most potential ways to implement AM in spare part production in critical infrastructure. This case selection provided us with the necessary data to model alternative scenarios in the critical infrastructure.

3.3. Analysis

With respect to availability-based maintenance, it is essential to minimize shutdown time. This requires the availability of replacement parts. For parts, the main review points are the delivery time and the suitability of the product, the latter being assessed by its dimensional accuracy and surface quality.

In the case of CAD modeling, the exterior dimensions and print volume were examined. On this basis, it was possible to determine how large a fraction of the spare parts the machines could print. Based on the print volume, the print time was simulated using each printers printing volume. The print run of a single track yielded an estimate for printing the whole range of spare parts for a product. Identifying the number of 3D printers allowed the amount of spare part production for all the pumps to be estimated.

Parts that have special requirements in terms of surface quality are challenging for AM production, which cannot, as a rule, meet these requirements. For this reason, such pieces have to be subjected to post-processing using subtractive methods, a point that needs to be observed in AM design. However, surface quality is not always critical to the function of the part. Therefore, the requirements for each piece per section need to be known. See also “From rapid prototyping to digitalization: Steps on industrializing additive manufacturing” (Ituarte, 2017).

4. RESULTS AND DISCUSSION

4.1. Results

In this study, the first research question dealt with how a change in the supply chain can be used to develop the technical resilience of a critical target. It was found that the supply chain can be understood as the external process of producing a critical object. The supply chain is a chain that combines suppliers of critical components with the distribution organization and the critical site (Bowersox et al., 2013).

The Hayes and Wheelwright (1984) product process matrix clarified the relationship between products and 3D printed parts in respect of the diversity of spare parts (Khajavi et al., 2014) for different technical items. In this case, it was possible to estimate the production by AM (Barz et al., 2016) when access to spare parts was prevented. When the technical object is simple and the cost of production is relatively low, product storage is sensible, and then the AM methods are not the best solution for recovery (Khajavi et al., 2014, Hayes & Wheelwright, 1984). In terms of the technical resilience (Carlson et al. 2012) of the critical object, the supply chain is currently push-controlled. The equipment is purchased according to a plan drawn up in advance, and maintenance is carried out in accordance with the agreed maintenance cycle (Moubrey, 1999), where the risks are managed by adjusting the size of the spare parts storage and the amount of replacement equipment.

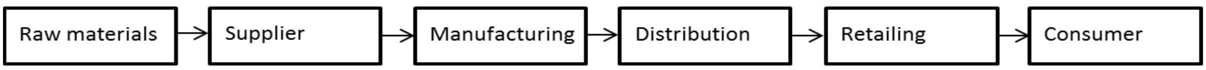

Figure 4.1 Traditional supply chain (Beamon, 1998).

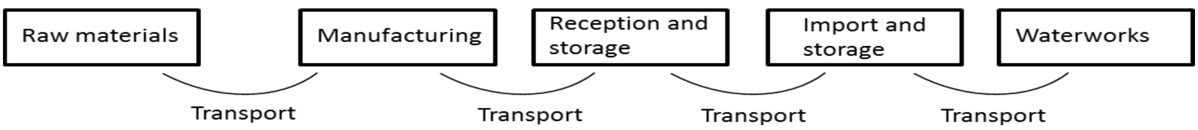

Figure 4.2 Waterworks spare parts supply chain (Sulzer Ltd, 2016).

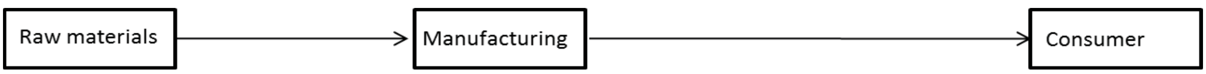

Figure 4.3 Additive manufacturing supply chain when parts are manufactured on site.

The study then further asked how the supply chain of AM can change the production of critical item spare parts. The analysis was carried out by modeling the key components of a single pump, evaluating the key parameters of the production method in the literature, and computing the printing event in simulation. Subsequently, key factors related to manufacturing and post-processing were analyzed.

In Finland, there are ten metal 3D printers, according to a list updated on October 20, 2017, some in a commercial, others in an educational context. Two of these were SLM Solutions machines, SLM 125HL and SLM280HL Twin. One is the Concept Laser MLAB cusing. Seven machines are manufactured by EOS, three being EOSINT Development machines, three EOSINT M 270 Xtended machines, and one EOSINT M270 (FIRPA, 2017). EOSINT development machine parameters are not available; therefore, it has not been possible to compare their production with other machines.

All metal 3D printers in Finland utilize the DMLS method (FIRPA, 2017), in which metal powder is applied to the building platform. The metal powder is subjected to laser energy, reconstructing the CAD model (Rapid Prototyping Services, 2017). The product is thus made of powder layer by layer (Gibson et al., 2014).

CAD models were made for the evaluation of the main components of the Sulzer pump, Sulzer AP-22-80 (Jaakkola, 2012), used for Hyvinkää water production. The main parts are described in the manufacturer's specifications, which also contain options for transferring parts between different pump models. The critical parts were the impeller, the shaft sealing, the casing cover, and the bearing unit (Sulzer Pumps, 2009). In addition, the volute casing part is the biggest critical part; it is made by casting. The part has a diameter of 560 mm, which makes it impossible to manufacture on any of the machines examined. It is possible to cast this part by polymer 3D printer in Finland (FIRPA, 2017). In the present study, only metal 3D printing has been investigated; polymer 3D printing was not simulated.

The dimensional accuracy of the part is crucial for the functionality of the part (Sulzer Pumps, 2009). The manufacturer of the pumps has specified that clearance may be up to 0.05 mm. The dimensional accuracy of DMLS technology depends on the material. The averaged tolerances for the most essential materials are within the required limits of precision. For tool steel, the so-called Maraging steel and Inconel material, the tolerance is 0.0508 mm (Rapid Prototyping Services, 2017).

Table 4.1 shows the size and printing time of each metal 3D printer in Finland. The information in the table is based on the equipment supplier's protocols. For all machines, regardless of the material selected, the maximum speed indicated by the manufacturer is selected.

Table 4.1 Critical spare parts printing times with different printers

3D PRINTER	3D printing volume	3D printing speed (max)	Printing time			
			Impeller 181,12 cm³	Shaft sealing 249,96 cm³	Casing cover 2243,62 cm³	Bearing unit 26,12 cm³
SLM 125 HL	125x125x125 mm³	25 cm³/h	7h 14 min 41 s	9h 59 min 54 s	Over- sized	1 h 2 min 41s
SLM 280 HL Twin	280x280x365 mm³	55 cm³/h	3h 17 min 35 s	4h 32 min 41s	40h 47 min 35 s	28 min 30 s
Concept Laser MLAB cusing	90x90x80 mm³	5 cm³/h	Oversized	Over-sized	Over-sized	5h 13 min 26 s
EOSINT M 270 Xtended	250x250x215	72 cm³/h	2h 30 min 56 s	3h 28 min 18 s	31h 9 min 41 s	21 min 46 s
EOSINT M 270	250x250x215	72 cm³/h	2h 30 min 56 s	3h 28 min 18 s	31h 9 min 41 s	21 min 46 s

4.2. Discussion

In an infrastructure that contains a large number of different spare parts that may be created by AM (Khajavi et al., 2014), the process has the potential for enabling a wider availability of spare parts (Berman, 2012) and should be brought into service as soon as possible when access to spare parts is curtailed or a technical item fails (Barz et al., 2016). AM's ability to be a part of the maintenance supply chain on as-needed basis provides excellent value for money.

The study has revealed that modern technologies enable the technical features of the object to be moved to digital format (Gibson et al., 2014). This enables the storage of spare parts in a digital library (Khajavi et al., 2014). The unlimited number of spare parts type CAD models can to be edited and relayed elsewhere if they are restored electronically. From a digital library, selected products can be made in advance or on demand by a 3D printer from selected material (Frazier, 2014). This makes it possible to produce parts near where they are required (Ituarte, 2017).

The study confirmed that it is essential for the technical resilience (Bologna et al., 2011) of a critical target that spare parts are available after a technical failure. The need for spare parts can arise unexpectedly. There is a large variance in critical infrastructure equipment, which creates the circumstances for precautionary risk management, leading to an extensive storage of spare parts (Valtioneuvosto, 2017).

Post-processing for prints affects the usability of the parts. The post-processing depends on the intended use of the product. The material from which the part is made substantially affects what post-processing can and needs to be done. (Gibson et al., 2014)

4.3. Methodological implications

In this case, the post-processing steps were evaluated for the products. In addition to time, post-processing also needs equipment and facilities. We did not evaluate costs, space, or sequential effects, but investigated the technical possibilities of manufacturing material to produce spare parts for a critical object. It was estimated that every piece of post-processing would last a few hours. This is not crucial in the timeline of 3D printed spare parts in the critical infrastructure. Still, it must be taken into account when planning the adoption of AM in spare parts production. The results of this study can be no more than indicative, because they concern only one case, and only the officially listed Finnish metal 3D printers were studied. Undoubtedly, there are 3D printers in the world, whose performance is significantly better than those used in Finland.

An expanded frame of analysis would permit more rigorous research and greater validity. This would encompass further case studies (Yin, 2009) and utilizing methods and ideas from complementary topics such as: Information system design research for building, improving, and testing artifacts, services, methodology, inventions, and emergent inventions, e.g., design research in information systems (Hevner & Chatterjee, 2010); a design theory for systems that support emergent knowledge processes (Markus et al., 2002), and systems development in information systems research (Nunamaker et al., 1991); reasonable action research for the investigation of organizational and work system change with service-artifact implementation (Baskerville & Wood-Harper, 1998); and a last-mile research approach for general utility production, which in the end addresses the value-building, high-value, real-world impacts and economic returns on a national and global scale (Nunamaker & Briggs, Toward a broader vision for information systems, 2011).

5. CONCLUSIONS

We reviewed the water pump manufacturer's claim of interchangeability of critical spare parts between different pump models and found that interchangeability was low or even poor. It is noteworthy that four of the five major spare parts identified by the manufacturer can be printed with metal 3D printers in Finland from the manufacturer's specified material.

The main general finding of study was that a material-enhancing manufacturing method can produce critical spare parts for a critical item. As a proof of concept, this study has shown that it makes sense to be prepared for critical situations by adopting AM for critical spare parts within the supply chain.

The challenge of precautionary risk management is that the material needs to be stored, because the defective part cannot be predicted. According to this study, preserving spare parts in the form of a digital library and printing them with a 3D printer makes it possible to quickly produce spare parts in a 3D production chain, thus enabling a reduction in the number of spare parts stored. The supply chain can also be shortened by bringing the 3D printers closer to the operations. Cost-effectiveness in preparedness increases and the security of supply improves as the supply chain shrinks. If the critical spare parts are produced near the waterworks, the largest threat defined—the disruption of spare parts—is removed from the critical maintenance processes, minimizing the interruption time. Dependence on external spare parts suppliers is reduced, which improves self-sufficiency. This improves the technical resilience of the object, e.g., the ability to recover from a fault. This requires that the infrastructure critical target supply chain be defined and redesigned, taking into account the potential for AM.

In respect of the technical equipment of the waterworks, the supply chain is push-driven. By implementing the basics of pull control for products that can be produced as needed by AM, adaptations to need are improved. With regard to push and pull control, the hybrid model is the best supply chain management method. In this case, the lead time decreases and the technical resilience increases.

The study has found that AM can be used to develop the technical resilience of critical infrastructure targets, the main advantages being shortened time and improved characteristics in the context of rapid recovery. In the adaptive phase of a severe disturbance, AM can initiate a fast recovery by starting the production of critical spares.

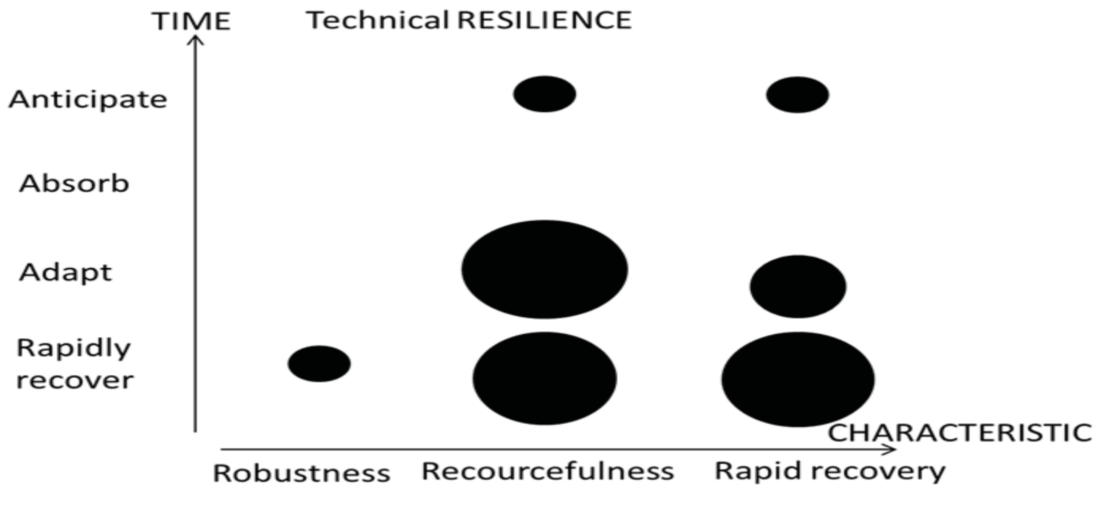

Figure 5.1 Enhancing technical resilience for critical infrastructure with AM classified by time and characteristics.

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