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Cross-industry exploration of product repair applications enabled by Additive Manufacturing

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Abstract

Repair activities could benefit from Additive Manufacturing (AM) technology as a result of the politically planned, continuous implementation of circular economy into European industry. AM provides novel opportunities with regard to design-optimized, tailored, and demand-specific, small batch size production. Thus, an exploration of industry perspectives for AM repair technology is needed to provide guidance and understanding of current opportunities and barriers of this promising technology in distinctive industries. A number of questions arise from the initial literature and background analysis: What minimum set of opportunities and barriers does exist for AM repair technology? What indicators could be used by companies to evaluate their product portfolio for AM repair? What is the minimum set of requirements for a more successful application of AM as repair method? What emerging AM tech repair applications are currently discussed in the community? This dissertation follows a methodology that includes a literature study, a quantitative data analysis, a set of exploratory interview and feedback interviews to answer those questions. Through it, this dissertation lays out the fundamental considerations necessary to achieve a cross-industry perspective on AM technology for repair and an analysis of industrial parts or products with regard to their AM repair suitability. Clustered by the dimensions company-strategy, business case, application and technology, a catalogue provides an orientation on the favorable characteristics and conditions for AM repair integration. It is found, that a classification can be made based on the repair actor (Industrial repair and consumer-enabled repair), the repair method (Spare part generation and direct product repair) and the repair technology (Polymeric and metallic AM). A minimum set of opportunities for AM repair technology includes organizational, process, ecological, logistics/stock and manufacturing aspects, whereas a set of barriers includes organizational, process, legal, cost and manufacturing aspects. Furthermore, changes are necessary to enhance the utilization of AM technology for repair applications. This includes the OEM and general manufacturer mindset change, pro-repair legislation changes, and AM technology visibility and integration. Lastly, it is found that multiple emerging AM tech repair applications are currently discussed in the community including predictive maintenance, decentralized repair, and improved 3D scanning and reversed engineering technologies. By answering these questions, this dissertation aims to elucidate the academic and corporate community on the wider considerations necessary for a deeper integration of AM technology in repair activities.

Sammandrag

Reparationsaktiviteter skulle kunna dra nytta av Additive Manufacturing (AM)-teknik som ett resultat av den politiskt planerade, kontinuerliga implementeringen av cirkulär ekonomi i den europeiska industrin. AM ger nya möjligheter när det gäller designoptimerad, skräddarsydd och efterfrågespecifik produktion av små batchstorlekar. Således behövs utforskning av industriperspektiv för AM-reparationsteknik, för att ge vägledning och förståelse för nuvarande möjligheter och barriärer för denna lovande teknik i distinkta branscher. Ett antal frågor uppstår från den inledande litteratur- och bakgrundsanalysen; Vilken minimiuppsättning av möjligheter och hinder finns för AM-reparationsteknik? Vilka indikatorer skulle kunna användas av företag för att utvärdera sin produktportfölj för AM-reparation? Vilka är minimikraven för en mer framgångsrik tillämpning av AM som reparationsmetod? Vilka nya AM-tekniska reparationsapplikationer diskuteras för närvarande i samhället? För att besvara dessa frågor följer denna avhandling en metodik som inkluderar en litteraturstudie, en kvantitativ dataanalys, en uppsättning av utforskande intervjuer och återkopplingsintervjuer. Genom denna metod lägger denna avhandling fram de grundläggande överväganden som är nödvändiga för att uppnå ett branchövergripande perspektiv på AM-teknik för reparation, och en analys av industriella delar eller produkter med avseende på deras AM-reparationslämplighet. En katalog grupperad enligt dimensionerna; företagsstrategi, affärscase, applikation och teknologi, ger en orientering för de gynnsamma egenskaperna och förutsättningarna för AM-reparationsintegration. Det visar sig att en klassificering kan göras baserat på reparationsaktören (Industriell reparation och konsumentaktiverad reparation), reparationsmetoden (Reservdelsgenerering och direkt produktreparation) och reparationstekniken (Polymerisk och metallisk AM). En minsta uppsättning möjligheter för AM-reparationsteknik inkluderar organisatoriska, ekologiska, process-, logistik-/lager- och tillverkningsaspekter, medan en uppsättning barriärer inkluderar organisatoriska, juridiska, process-, kostnads- och tillverkningsaspekter. Dessutom är förändringar nödvändiga för att förbättra användningen av AM-teknik i reparationsapplikationer. Detta inkluderar förändringar i OEM och den allmännatillverkares tänkesätt, förändringar i lagstiftningen för reparation och synlighet och integration av AM-teknik. Slutligen har det visat sig att flera nya AM-tekniska reparationsapplikationer för närvarande diskuteras i samhället, inklusive prediktivt underhåll, decentraliserad reparation och förbättrad 3D-skanning och omvänd teknik. Genom att besvara dessa frågor syftar denna avhandling till att belysa den akademiska världen och företagsvärlden om de bredare överväganden som krävs för en djupare integration av AM-teknik i reparationsaktiviteter.

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List of Abbreviations

3DPR	3D Printing for Repair
AM	Additive Manufacturing
CE	Circular economy
EU	European Union
OECD	Organization for Economic Co-operation and Development
WEEE	Waste from electrical and electronical equipment

1. Introduction

1.1 Background

Considering current environmental research production and consumption patterns significantly contribute to the carbon dioxide emissions (Arias, et al., 2021) (Blanco, et al., 2014, p. 367). A transition to new patterns is needed to transform global economies and societies and ensure a sustainable existence on Earth. At high political levels in Europe, sustainable development has also become a critical agenda point being a decisive factor for citizens' political vote (Radowitz, 2019). Introduced in 2019, the European Green Deal is intended to make the first climate-neutral continent and strengthen its economy in a sustainable way. The European Union (EU) concretized the Green Deal in 2020 by adopting one of its building blocks, the new circular economy (CE) action plan. This is planned to leverage circularity and CE initiatives, aiming at maximizing the resource efficiency (European Commission, 2021). Furthermore, businesses are increasingly under pressure by enforced legislation and economic consequences of the Paris Agreement (Malmqvist, 2020). The consequent economic shift towards more sustainable products and services is also driven by present and future customer demand and results in substantial risks for companies. Also, this shift is politically linked to the integration of CE.

This thesis will focus on repair applications. Because of their positive economic and ecological effects, repair applications are impactful activities that are also addressed by the European Union. These applications slow down resource loops by prolonging product life time before additional energy input (e.g., for recycling purposes) (European Parliamentary Research Service, 2019). An study by the Organization for Economic Co-operation and Development (OECD) from 2018 proposes that CE provides novel economic opportunities for the repair sector on a global scale. The publication argues that being an early adaptor of CE technology could be decisive for future economic success (McCarthy, et al., 2018).

EU legislation moving to strengthen "Right to Repair" rules in order to cease premature product obsolescence and penalize companies that offer unsustainable products (Smith, 2020). Premature product obsolescence is the result of deliberate decision-making of manufacturers with regard to the product design, manufacturing, assembly or service leading to the provoked limitation of the product life (Right to Repair Europe, 2021). By gaining access to spare parts, local and independent repair services or private persons could perform repair activities, consequently increasing the product life and reducing high-value waste. Similarly, industrial partners or original manufacturers could utilize developments around the "Right to Repair" for the creation of a market around repair activities.

A broad summary and analysis of industrial perspectives is needed to understand today's AM repair applications and their future potential. The questions of what potential can be leveraged by Additive Manufacturing to drive repair applications for industrial goods and how can this potential be evaluated for products and industries are highly relevant in that context. The identification of suitable industries or products is required to drive business development and integrate AM technology and transition from theoretical AM capability analysis to practical value analysis in economies, driving sustainability in the years to come.

1.2 Research Gap and Research Questions

Based on the literature pre-study and stakeholder communication in the research field, the following gaps were identified:

- Missing analysis of AM repair applications for various product classes or industries;
- Missing analysis of decisive factors for successful AM repair applications;
- Missing industry perspectives on future perspectives 3D printing in repair applications.

The subsequent hypothesis can be formulated: *With its capabilities and limitations, AM provides a high repair potential suitable for a selected number of European products and industries.*

The overarching question can be formulated: *What potential can be leveraged by Additive Manufacturing to drive repair applications for industrial goods is relevant – and how can this potential be evaluated for products and industries?*

The derived research questions can be clustered as follows:

- *What minimum set of opportunities and barriers does exist for AM repair technology?*
- *What indicators could be used by companies to evaluate their product portfolio for AM repair?*
- *What is the minimum set of requirements for a more successful application of AM as repair method?*
- *What emerging AM tech repair applications are currently discussed in the community?*

1.3 Purpose

Purpose of this thesis work is to link academia to practical needs and knowledge. The objective is to generate practical and useful answers that are applicable by companies to evaluate AM repair technology and enable implementation. By sourcing information from academic research and interviews, this thesis project will bridge gaps between theory and practice.

The outcomes of this thesis will be the following:

- Classification of AM Repair dimensions;
- Overview of opportunities and barriers;
- Industry comparison;
- Conditional changes needed to drive AM for repair;
- Indicative assessment guide for companies to evaluate AM repair potential of products.

1.4 Delimitations

A concretized thesis scope is a decisive factor for defining the methodology and the boundaries of the system to be analyzed:

To be included into this study are the following points:

- Central-European perspective consisting of high-wage countries and the common supranational framework “European Union” (Brecher, et al., 2011, pp. 23-26), (European Parliamentary Research Service, 2019), (Closa & Kochenov, 2016);
- Voices from various industries to be reflected based on interviewee selection as part of methodology; link between academia and industry;
- Repair potential for both AM and non-AM products – to be compared as part of the thesis;
- Metallic 3D printing and polymeric 3D printing – to be compared as part of the thesis.

To be excluded from this study are the following points:

- Reverse engineering activities;
- Business case calculation;
- Design strategies and detail comparison of Design for Repair, Design for Remanufacturing or other paradigms;
- Technical comparison of AM processes;
- Biotechnological application of AM for repair purpose (bone repair, tissue repair, etc.).

1.5 Methodology

The methodology follows an exploratory, multi-step approach which is divided into three clusters:

(1) Information gathering: Literature review, data analytics and interviews will provide a solid understanding of the subject.

(2) Framework creation: An indicative framework will be created based on the three data inputs.

(3) Framework refinement: This framework will be refined through a second round of interviews, the feedback interview.

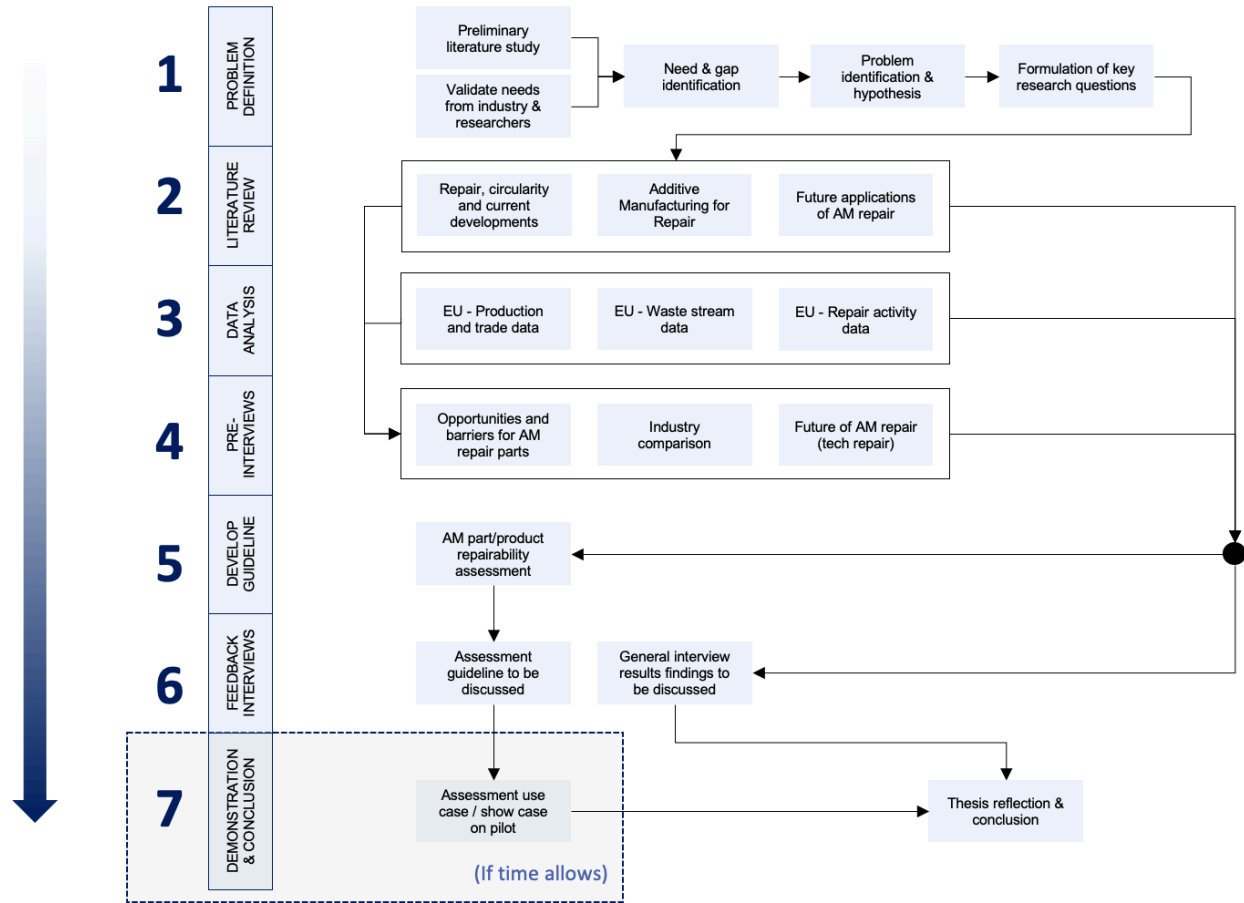


Figure 1: Master's thesis methodology structure

The Figure 1 depicts the methodological approach chosen for this Master thesis project. It highlights the input of three sources: the literature review, the data analysis and the interviews. As visible in the figure, the assessment use case and direct implementation of the framework is not part of this thesis due to time constraints. The potential next steps based on the research results of this thesis are presented in 4.4 Recommendations and future work.

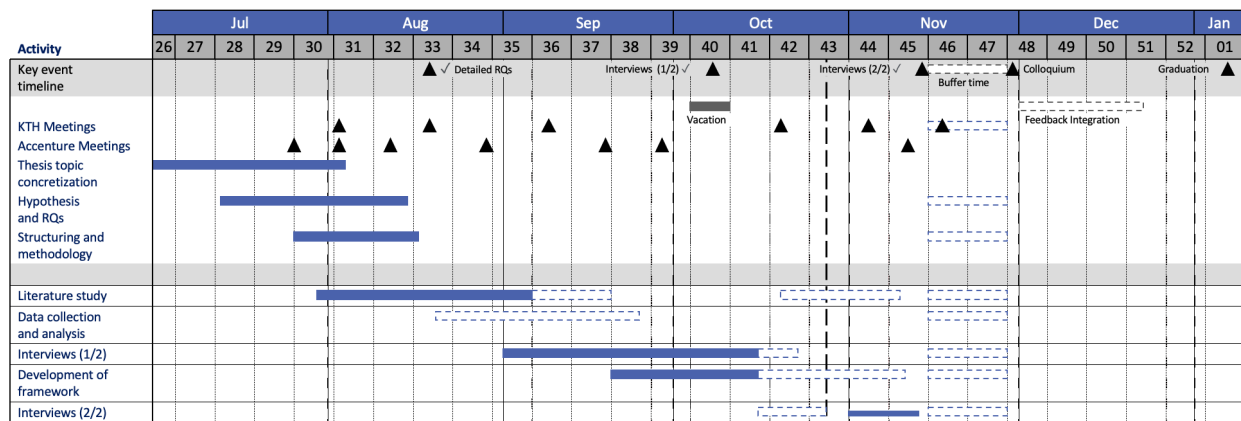


Figure 2: Project plan for the Master's thesis

Furthermore, a project management approach with segmentation of steps, intermediate goals and deadlines will serve as auxiliary methodology, enabling progress and ensuring scoping and activity durations according to plan. This is shown by the project plan in Figure 2. By inserting quality gates and transition times between the scheduled sprint periods, the plan remains both directional and flexible at the same time.

2. Information gathering

2.1 Literature Review

During the preliminary literature review, various key areas were identified for further investigation. The results of those investigations are summarized in the subsequent chapters.

2.1.1 Repair activities – Political and academic significance

In academia, one prominent publication links CE to its ten core activities. This concept is synonymous with the CE strategies of refusing, rethinking, reducing, reusing, repairing, refurbishing, remanufacturing, repurposing, recycling, and recovering (Kirchherr, et al., 2017, pp. 221-232).

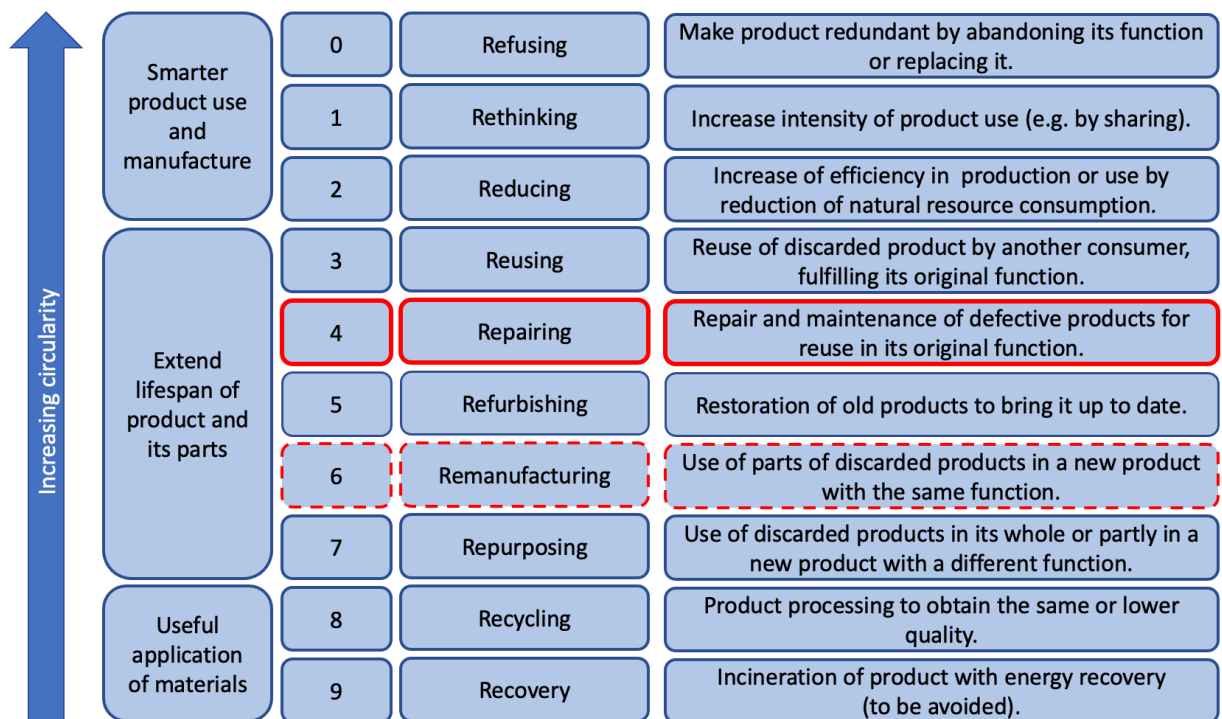


Figure 3: Circular economy concept based on (Kirchherr, et al., 2017, pp. 221-232)

The visual differentiation among the various forms of CE is depicted in the figure 3. It includes a variety of activities ranging from material recycling and energy recovery to refusing, rethinking or reducing of a product use with increasing circularity. This indicates that a smarter product use and manufacture has a higher circularity impact than the extension of product and part lifespan or the useful application of materials. As indicated in figure 3, repair and remanufacturing are linked as repair activities are an integral part and enabler of remanufacturing processes. Consequently, this thesis indirectly also contributes to better understand remanufacturing (Kandukuri, et al., 2021).

At political levels, circularity is highlighted as potential part of the business, production and consumption transformation given the urgent need for climate action that is proclaimed by scientists (Hagedorn, et al., 2019).

In the EU, repair markets vary by member state and type of product. With a high number of actors this field is constituted of consumers, retailers, manufacturers and suppliers. A study EU Commission study regarding the socioeconomic implications of increased product repairability shows that repair service providers mentioned common barriers that hinder further penetration into the market. Those investigated barriers included the “ lack of access to spare parts, technical information, diagnostic software and training [...], [the] lack of standardization and interoperability of key components across brands [...], [the need for] increased technical knowledge [...], [the] technical barriers making repair impossible due to product design, technical specifications, the choice of materials and components, or to the difficulty of disassembling components [...] [as well as the] unattractive price of repair due to the high price of labour [...]” (Deloitte; Directorate-General for Environment (European Commission); ICF-GHK; SERI, 2016).

At the same time, an EU study of 2018 about the consumer engagement in the circular economy indicates that 64 % of consumers always repair broken or damaged products. The three main reasons for not repairing were linked to the excessive price of repair, the preference for new product and the notion of having an obsolete or out of fashion product.

Furthermore, the product repair could provide positive effects for people and the planets, as money could be saved, a product replacement could be postponed, waste could be reduced, the use of resources could be optimized, and product life prolonged by increasing the circularity (European Parliamentary Research Service, 2019).

In the academic literature, repair activities are also analyzed by investigating the user motivation and barriers. Those insights are obtained for a better understanding and more successful application of repair services in the future. In the Users’ motivation and barrier model, Terzioglu-Ozkan identifies and contrasts various motivation and barrier factors, segmented into technical aspects (e.g., required knowledge, skills or time), emotional aspects (e.g., perceived pleasure, negative feelings or environmental concerns), and value aspects (e.g., financial factors, aesthetic value or functional value) (Terzioglu-Ozkan, 2021).

Based on this publication and the given overview of design repair methods, a simplification of AM repair into “AM spare parts generation” (compare “3D printing product parts”) and direct repair (compare” 3D printed patches” and “3D printed pen”) can be made (Terzioglu-Ozkan, 2021, p. 6).

2.1.2 Opportunities and limitations of AM for repair applications

Based on the literature review, the opportunities and limitations of using AM technology for repair applications will be summarized in this chapter.

Using AM technology for repair applications has been part of academic research work. Linking repair and AM is relevant, as the AM technology provides multiple advantages the need for quick supply of broken components can be fulfilled by AM at an increasingly higher quality and lower cost. Repair is relevant to increase part availability by distributed manufacturing and reduce stock and inventory enabling on-demand production. AM enables the realization of lightweight design, e.g., honeycomb or mono-coque structures by processes like direct energy disposition creating a foundation for automated repair and restoration (Wahab, et al., 2019).

For metal additive manufacturing, Vafadar describes challenges and potential for repair in a recently published article: The given advantages of AM technology include the realization of complex shapes, the reduction of material waste and lowering the need for specialized tooling. By that, AM overcomes conventional manufacturing downsides and presents itself as technology of new possibilities.

On the opposite side, the challenges range from the limitation of production volume, standards compliance, post-processing, product quality, maintenance and material compatibility aspects. Despite the abovementioned potential, industries still struggle with the adoption of these possibilities. (Vafadar, et al., 2021). Furthermore, Wahab adds that these lightweight structures could be more fragile and thus face a higher risk of damage. This is complemented by a lack of guidelines that is elaborated on as a central barrier.

Despite all mentioned advances for repair and also for remanufacturing (see 2.1.1 Repair activities – Political and academic significance), the lack of awareness among customers, the process efficiency, the access to technology and skilled labor, the lack of effective collection of used or broken parts as well as the reluctance on manufacturer side to launch repair or remanufacturing business models leads to a large gap between the theoretical and the gained value. In summary, this paper provides a set of design guidelines for different phases of repair and remanufacturing, adding to the foundation for the development of new guidelines (Kandukuri, et al., 2021). Similar points are made by Wahab et al in a paper from 2019 that highlights the need for D4X design guidelines for repairability (Wahab, et al., 2019).

2.1.3 Existing AM repair applications

AM is already implemented and part of manufacturing activities in various industries. Figure 4 indicates that the automotive industry, the aerospace industry and the industrial machines industry sum up to the principal part of the potential. Also, consumer products, the medical field and military/defense industry contribute to a wide-ranging integration of AM.

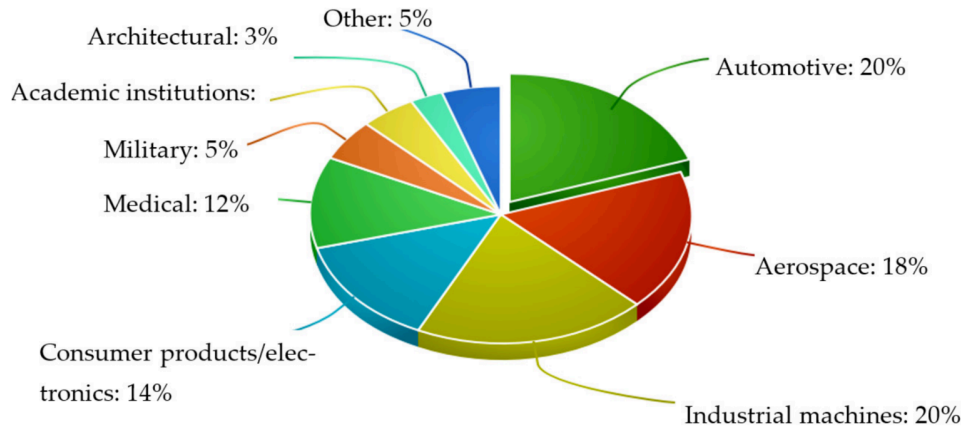


Figure 4: Industrial Adoption of AM based on Vafadar, et al., 2021, p. 2

Repair applications are investigated for instance by the European research project “Sharepair” that focuses on 3D Printing for Repair (3DP4R) and consumer enablement for repair activities in a smaller scale (e.g., in repair cafes). The project aims at the reduction of waste from electrical and electronical equipment (WEEE) by facilitating digital tools and explore the potential of 3DP4R. WEEE is identified as the fastest growing waste stream in the European Union (SHAREPAIR Initiative, 2021).

This project explores the individual potential of specific WEEE products ranging from high-value mobile phones to lower value coffee machines. Data-driven research which is based on the evaluation of repair types from a database concluded that 7.5%-29% of repair café products might benefit from AM spare part (Samenjo, et al., 2021).

2.1.4 Future AM repair perspectives

Investigations with regard to future tech repair applications of AM led to three prominent topics that are currently subject of academic and media coverage. Firstly, in the subsequent section, the literature findings will be depicted. Secondly, those three topics serve as technology for the interview in order to stimulate additional responses, enlarging perspective on current academia and industry estimations.

1 - Autonomous repair – “Self-maintaining city”

Delivered by drone or robotic device, this service is a vision of a self-maintaining city (P., 2018), (Smith, 2018). The objective is to enable autonomous 3D printer units to repair infrastructure and environmental deterioration and by that minimize disruptions and negative implications for the human being (Robertson, 2020). Milestones like the project work from the United Kingdom project “Zero Disruptions” from streetwork show the potential of this technology integration. This project aims at developing robots as minimally invasive technology to maintain the infrastructure in United

Kingdom cities by 2050. Linked to that, 3D printing asphalt for road repairs is being developed and tested (Self repairing Cities, 2018), (Jackson, et al., 2018).

2 - Sensors in AM products for repair and maintenance

The application and integration of sensors into AM technology processes is a relevant field of research. The application of 3D-printed sensors is investigated by Khosravani et al in a study from 2020. According to Khosravani et al and based on their usage, those printable sensors can be classified into engineering use sensors and medical use sensors with the engineering sensors including mechanical, temperature, particle, and tactile sensors (Khosravani & Reinicke, 2020). The utilization of sensor data is closely linked to the concept of a “digital twin” or “virtual twin”. A digital twin models, visualizes, predicts and provides live as well as predicted feedback on property and performance. This technology could have significant cost-reductive and climate-positive effects by optimizing maintenance efforts in industrial settings. This strong relationship between digitization and AM is evinced by a recent thought-leadership publication (Keeble, et al., 2021).

3 - 3D printing in deep-water/space repair applications

AM technology with repair application focus is used both for deep-water and space environments. Those two environments share remoteness and limitations of material and equipment availability. Currently, underwater pipeline repair is being developed and commercialized in Norway. The project aims at the deployment of commercial applications and operations in late 2021 avoiding cumbersome, manual clamp repair by utilizing a robot for inspection and maintenance. In the article, in particular one advantage is highlighted: the realization of repair with the same material of the flowline (Maslin, 2021).

There is an active research community around space applications of AM for generation of parts, maintenance and repair. With the development of a high-temperature 3D printer for the International Space Station, a milestone has been reached. The exploration of out-of-Earth manufacturing methods beyond the current production limitations of 3D printers is planned to be tested on lunar missions (Sertoglu, 2021), (European Space Agency, 2021). Research on how to build and maintain a lunar or Martian infrastructure based on regolith is currently investigated (Isachenkov, et al., 2021), (Sertoglu, 2021), in parallel with the investigation of repair of in-orbit structures and machinery (Listek, 2021).

2.2 Data Analysis

Complementing the literature view on the topic as well as the pre-thesis scoping, this chapter will describe a data-driven approach to support the interviewee selection process and to underline the significance of the thesis topic by quantitative data. All utilized data are publicly available on the

EU databases “Eurostat” (European Commission, 2021). The analysis was performed utilizing python via Anaconda as an open-source distribution.

The general outcome can be summarized as follows:

- The production and trading volume has been increasing in the last decade with a positive trend for the future;
- Consequently, in correlation with more products produced, the amount of waste increases;
- The majority of repair performed activities converge towards the automotive, aerospace, and maritime industry as well as machinery manufacturing industries. This result will influence the choice of interviewees for this thesis methodology.

2.2.1 Production and trade data

The data of production and trade of goods sourced and compiled by Eurostat indicates the development of product volume for import as well as export purposes. Furthermore, it contains information regarding the number of manufacturing companies within the European Union. The source data is labeled as “Prodcom EXT_TEC09 / Trade by NACE Rev. 2 activity sector” (Eurostat, 2021). Additional metadata information is given online (Eurostat, 2021).

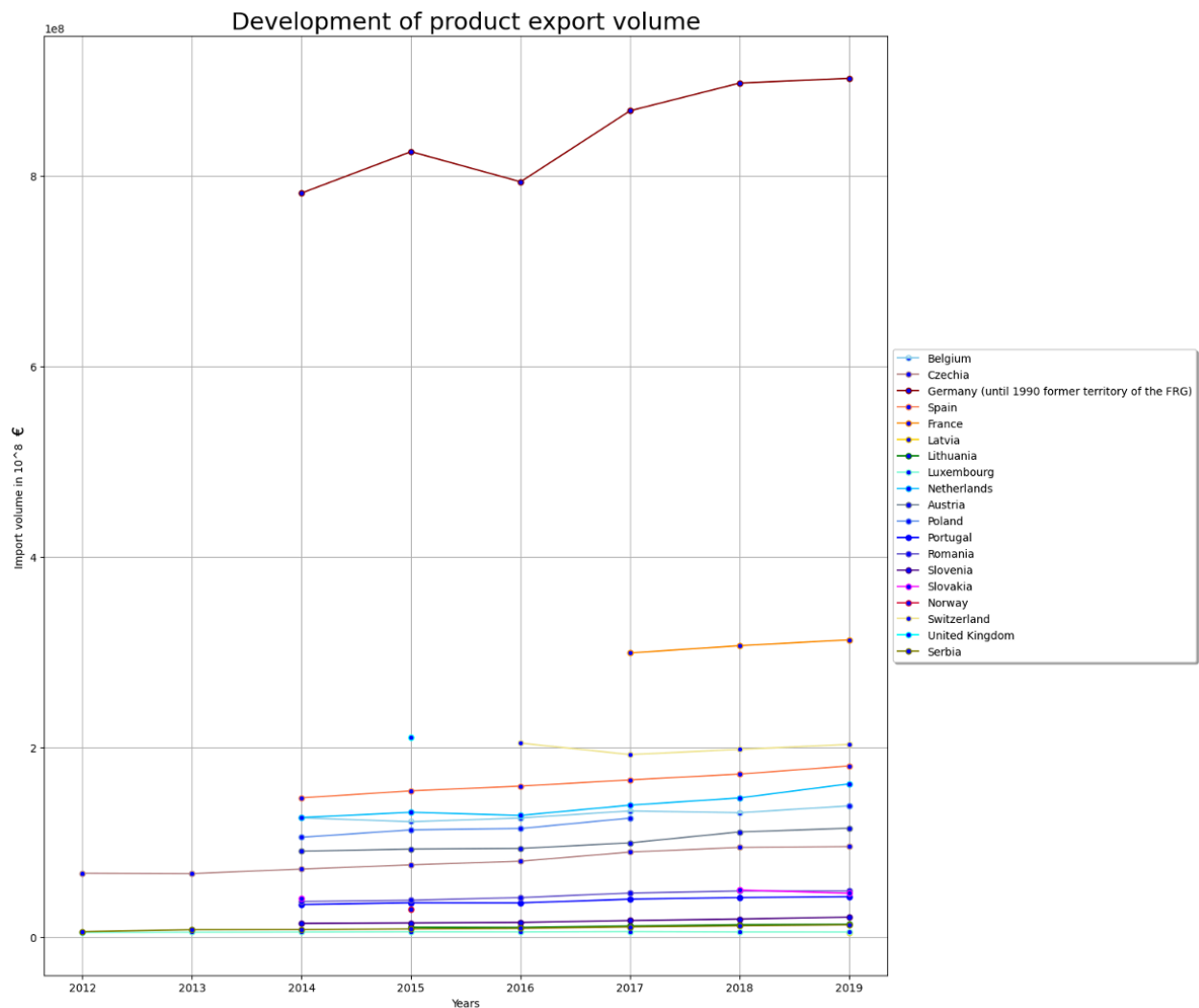


Figure 6: Development of product export volume in the European Union from 2012 to 2019

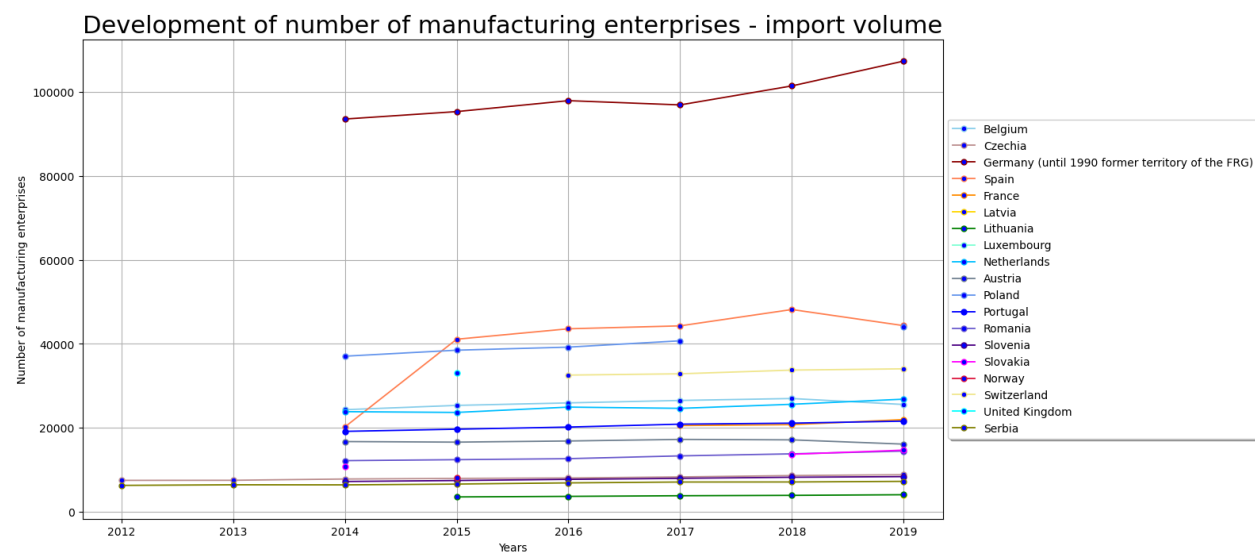


Figure 7: Development of importing volumes manufacturing enterprises by number within the European Union from 2012 to 2019

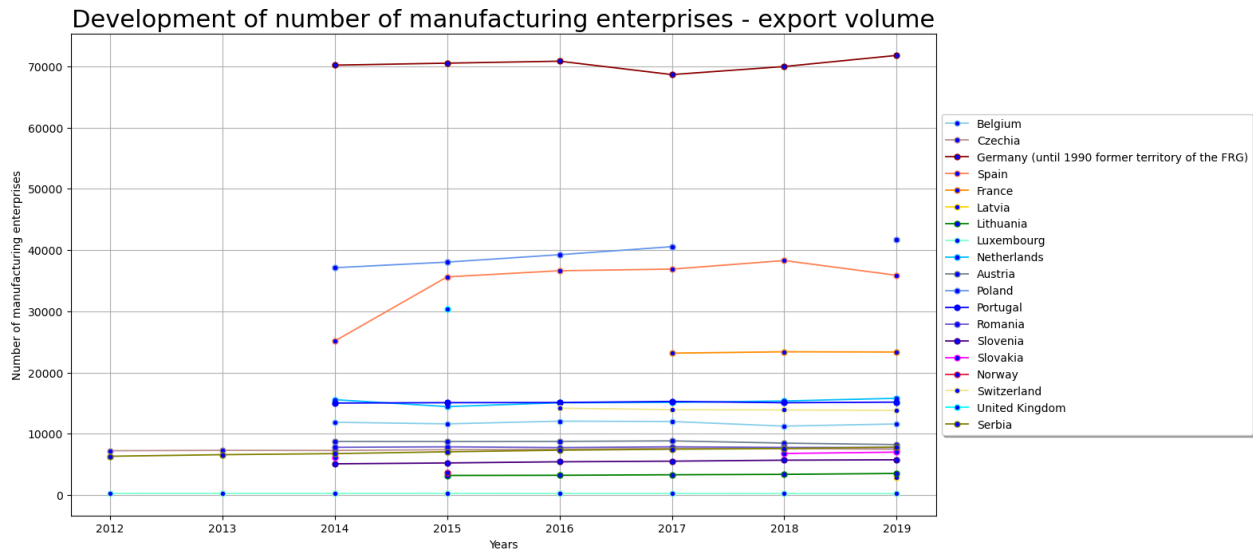


Figure 8: Development of exporting volumes manufacturing enterprises by number within the European Union from 2012 to 2019

The figures above indicate a stable with even a rising tendencies in some cases like for Germany, France or Poland, both for the number of manufacturing enterprises and the product import and export volume.

2.2.2 Waste stream data

The waste stream data sourced and compiled by Eurostat indicates the development of electrical and electronic total waste in tons in the European Union (consisting of 28 member countries) from 2004 to 2018. It contains information regarding the manufacture of computer, electronic and optical products, electrical equipment, motor vehicles and other transport equipment, including both hazardous and non-hazardous waste. The source data is labeled as “ENV_WASELEE” (Eurostat, 2021).

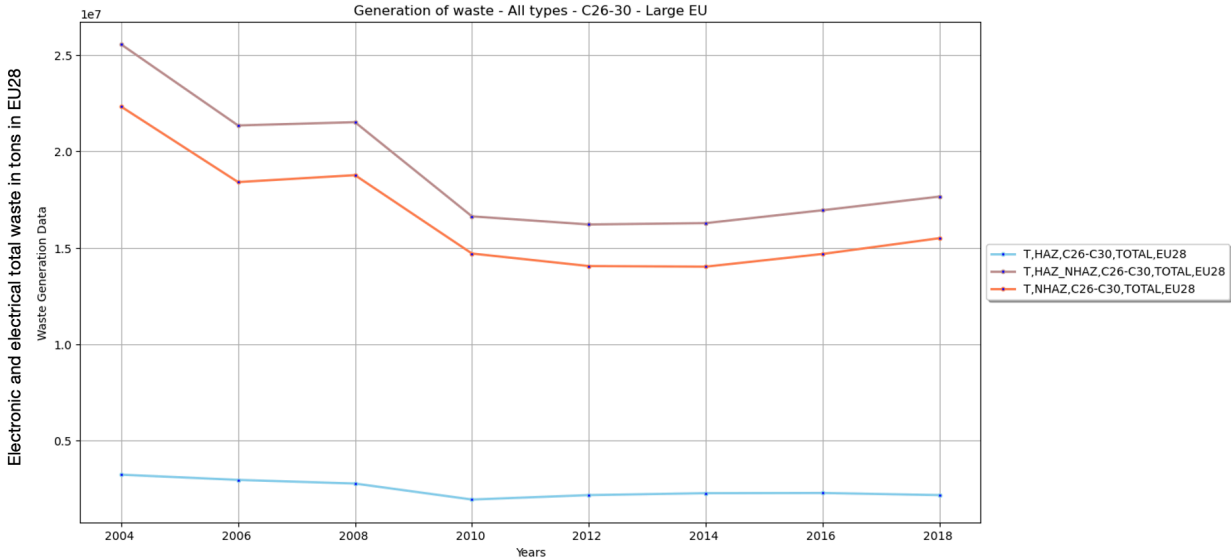


Figure 9: Electronic and electrical total waste in tons within the European Union from 2004 to 2018

The Figure 9 depicts the generation of electronic and electrical total waste in tons in the European Union from 2004 to 2018. From the graph, a decline tendency can be withdrawn from 2004 until 2012. After 2012, this tendency turns and becomes a steady incline of waste figures. This is supported by other sources proclaim stating electrical and electronic equipment waste to be one of the fastest growing waste streams in the European Union (European Parliamentary Research Service, 2019).

2.2.3 Repair activity data

The data of repair activities in the European Union sourced and compiled by Eurostat indicates the development and volume of distinctive repair services. The source data is labeled as “NACE Rev. 2 activity sector” (Eurostat, 2021). NACE Rev. 2 is the second revision of the statistical classification of economic activities in the European Union. Additional metadata information is given online in the Eurostat data library or in the predefining metadata document (Eurostat, 2008).

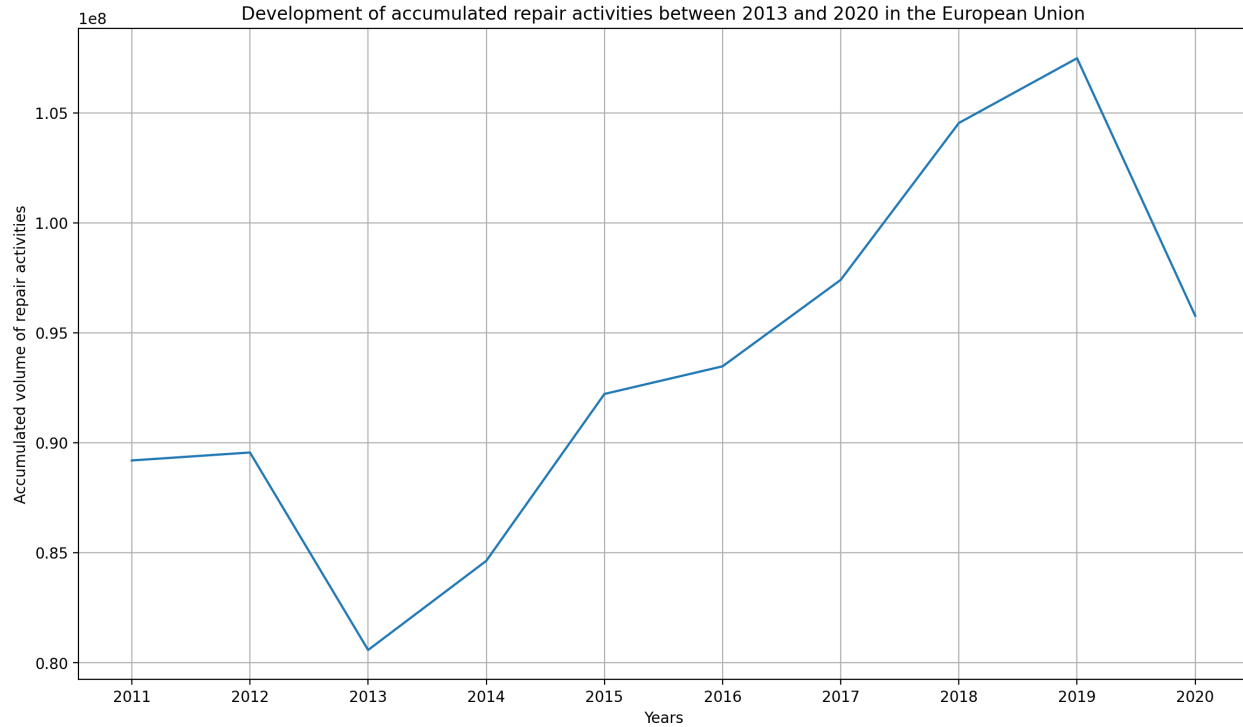


Figure 10: Accumulated volume of repair activities within the European Union from 2013 to 2020

The Figure 10 indicates the development of the accumulated volume of repair activities within the European Union from 2013 to 2020. Acknowledging a strong fluctuation from 2011 to 2013, then an increase tendency of repair activities becomes visible until 2019. The decline in 2019/2020 can be explained with the Covid-19 pandemic with strong, negative economic implications. The overall positive tendency of repair activities supports the relevance for research in that field and illustrates the economic opportunities of repair models.

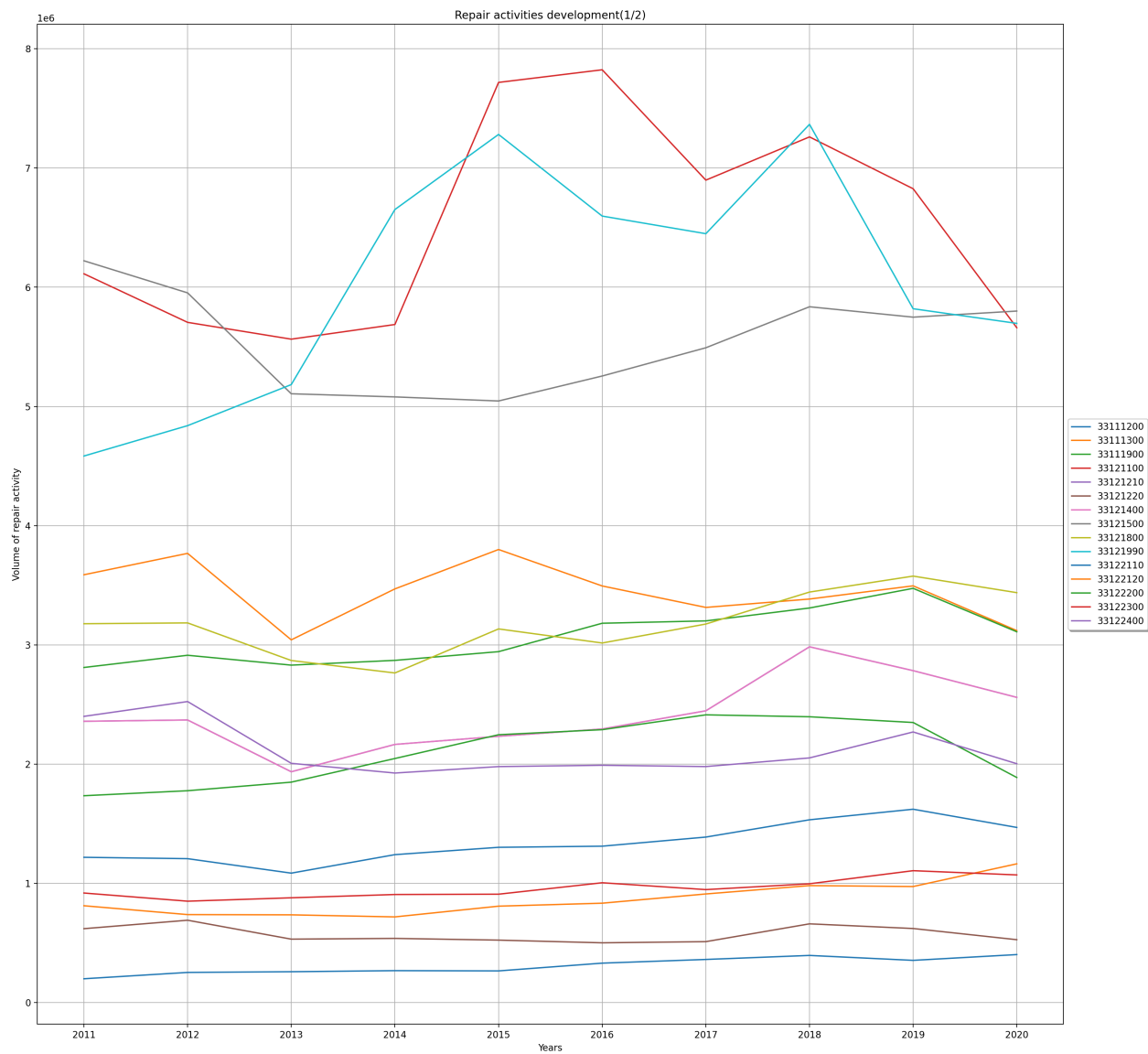


Figure 11: Volume of repair activities within the European Union (in EUR) from 2011 to 2020 (1/2)

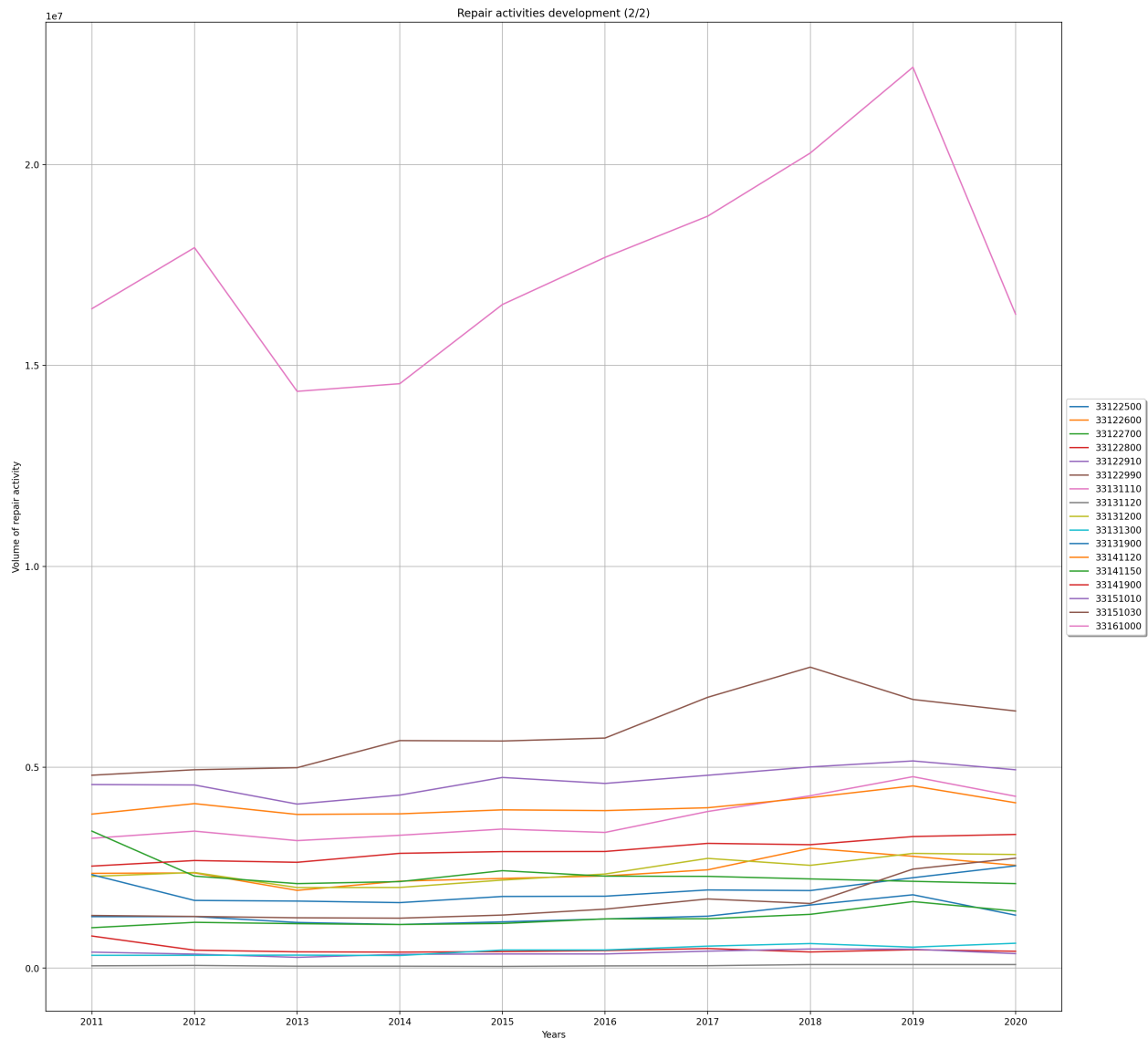


Figure 12: Volume of repair activities within the European Union (in EUR) from 2011 to 2020 (2/2)

Both figures, Figure 11 and Figure 12, indicate the economic volume of different sets of repair activities within the European Union from 2011 to 2020. Based on the database metadata, the repair activities with the largest volume could be identified and visualized. The following list illustrates and orders the highest volume repair activities:

- 33161000: Repair and maintenance of civil aircraft and aircraft engines;
- 33121100: Repair and maintenance of engines and turbines (excluding aircraft, vehicle and cycle engines);
- 33121990: Repair and maintenance of other general purpose machinery;
- 33122990: Repair and maintenance of other special-purpose machinery;
- 33121500: Repair and maintenance of lifting and handling equipment;
- 33151010: Repair and maintenance services of ships, boats and floating structures.

This identification of high-volume repair services allows general conclusions for the selection of suitable industries and stakeholders for the interviews.

2.3 Interview

2.3.1 Interview guideline development

Based on the proposed methodology, two interviews will serve as information input from industry perspective. For displaying the interview approach compactly in detail, the 7W questions of Kaizen method will be used. This tool is based on Kaizen methodology and allows to summarize a project's core information and here to characterize the guided interview (Melzer, 2015).

7W Questions	Response
What has to be done?	Data collection about current utilization, opportunities and barriers of Additive Manufacturing for repair purposes in various industries.
Who has to do it?	Nico Albrecht, thesis author and Master student – together with various stakeholders from academia and industry.
Why should it be done?	Data collection as foundation for the knowledge transfer and for answering the research questions of this Master thesis.
How is it done?	Anonymous interview with one data input interview and one follow-up interview for feedback. The author follows the framework of an exploratory interview approach with guiding questions.
When should it be done?	Data collection planning phase of the thesis in September and October 2021; for the feedback interviews in early November 2021.
Where should it be done?	Online with (Video) Call Services.
Why can't it be done differently?	Given the limited time frame of the thesis project, the author chose an explorative interview approach with guiding questions to provide a broad, multi-industrial view on the relevant research questions.

Development of methodology

In the following paragraph, an interview framework for the thesis project will be defined. It serves to provide a structure and comparability for otherwise highly qualitative interview results. The interview methodology follows a structure that is suggested in research academia with exploratory

elements, so additional background of the provided information can be well understood. The guideline followed the academic proposal “as open as possible, as structured as necessary” (Helfferich, 2019). As a consequence, the duration of an interview varied between 30 and 75 minutes.

Data privacy aspects

The interview series was set-up as anonymous interview. Complying with company requirements, personal data could not be subject of response and needed to be avoided. Furthermore, the interviewee was provided with the Data Privacy Information Document” as well as the interview guideline prior to the meeting. The data privacy document can be found in the appendix [Appendix 1].

Identification of valuable questions

The identification of valuable questions guiding towards a response to the formulated research questions is crucial. The literature study provides a strong foundation and orientation in current academia. But only the interviews can practical insights to gain transversal depth and link academia to the business world.

The designed interview questionnaire was designed aid for the interviewer and necessary structure to foster comparability, containing the following segments:

- Part 0: Self-Assessment;
- Part 1: General AM repairability potential & barrier assessment;
- Part 2: Repair scenario assessment for products and industries - AM, and non-AM parts;
- Part 3: Requirements, characteristics, and potential assessment for parts;
- Part 4: Emerging tech and future AM repairability solutions.

The extensive interview question catalogue is attached in the appendix [Appendix 2].

2.3.2 Interviewee selection

Based on the scoping of the thesis as well as data analytics results, the setting for the interviews and prominent industries to be included. The relevant industries were identified based on the literature study and the industries with high integration of AM (compare Figure 4) as well as the data analysis from EU datasets.

Stakeholders were identified and contacted through the following channels:

- Accenture network;

- University network;
- Internet (e.g., LinkedIn or company contacts);
- Author’s network.

Two factors were given particular attention for the selection and were added as self-assessment section in the beginning of each interview:

- Knowledge about additive manufacturing and repair applications;
- Academic or industrial background in that field.

Master Thesis - Interview Partners		
	Academic actors	Industry actors
Number	4	13
Background	(1) University professor	(1) Automotive
	(2) PhD candidates	(3) Aviation
	(1) Researcher at an institute of applied sciences	(2) 3D printer manufacturer
		(2) 3D printing service provider
		(5) Cross-Industry / Consulting (Consumer goods, Industrial equipment, Marine, Energy, Defense, Rail, Oil & Gas)

Figure 13: Interview partner characterization

The Figure 13 shows a characterization of the interviewees providing their background and quantification. As the aim is to provide a bridge between academia and industry this link was given a particular attention. With 27 stakeholders contacted, the response rate led to 17 interviews, four of which with academic profession and 13 of which with industrial background. During the interviews voices from various industries were heard indicating current implementation, ongoing research and further future potential of AM repair applications.

2.3.3 Interview conduction

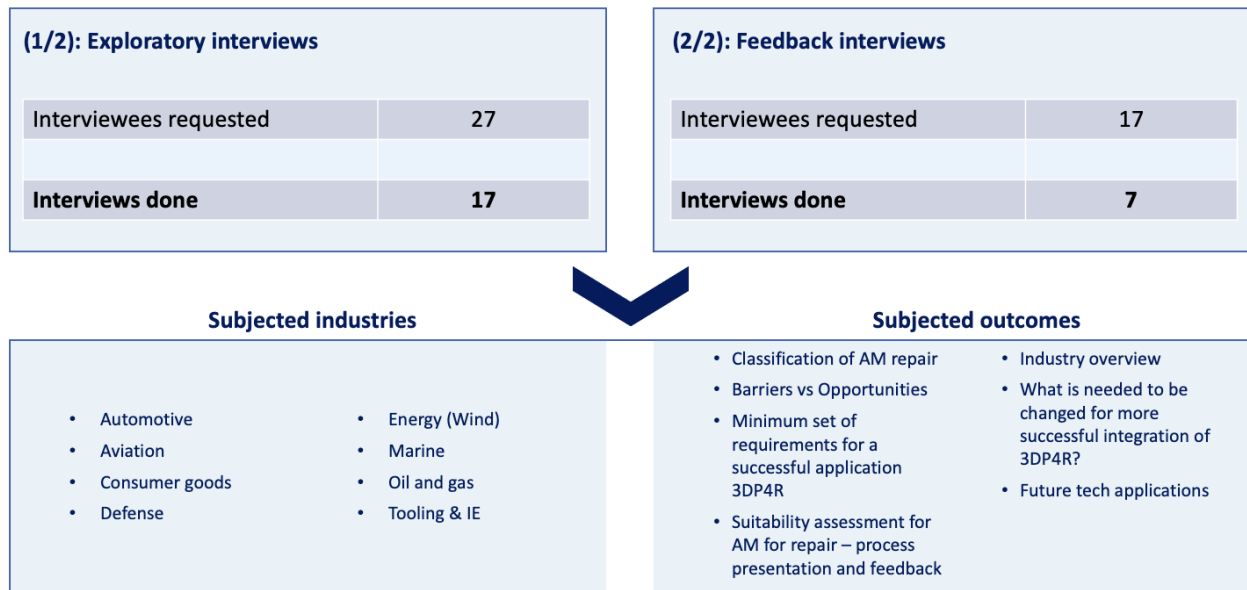


Figure 14: Interview details and outcomes

The Figure 14 describes the succession, details and topical outcomes of the interviews. The methodology contains the exploratory interview as main input source. With 17 interviews conducted and seven feedback interviews, a broad view on the topic AM and repair applications has been drawn. From the given perspectives the interview insights are limited to the list of industries on the left. The responses to the guiding questions enable the author to cover the subjects on the right.

Due to the selection and limited number of interviewees, the results must be seen as indicative and subjective to individual perspectives. The second interview serves as feedback and reflection opportunity, enabling a deeper discussion of the summarized preliminary results. Furthermore, the interviewees are invited to communicate constructive critical thoughts. This methodology provides a validation and additional input loop. The author aimed at concluding as many feedback interviews as possible. Due to time constraints as well as limited availability of original interview partners seven out of 17 original interviewees could participate in the feedback process.

3. Results

3.1 Interview results

The subsequent paragraphs will cover the results of the interviews that are condensed and clustered. In general, the interviewees agreed in their positive views regarding AM's suitability for repair applications despite acknowledging multi-dimensional limitations. These depend on the specific type of application. Thus, a clear definition and segmentation of AM and repair applications need to be clearly outlined at the beginning of the process. Figure 15 visualizes the classification that is supported by definitions below.

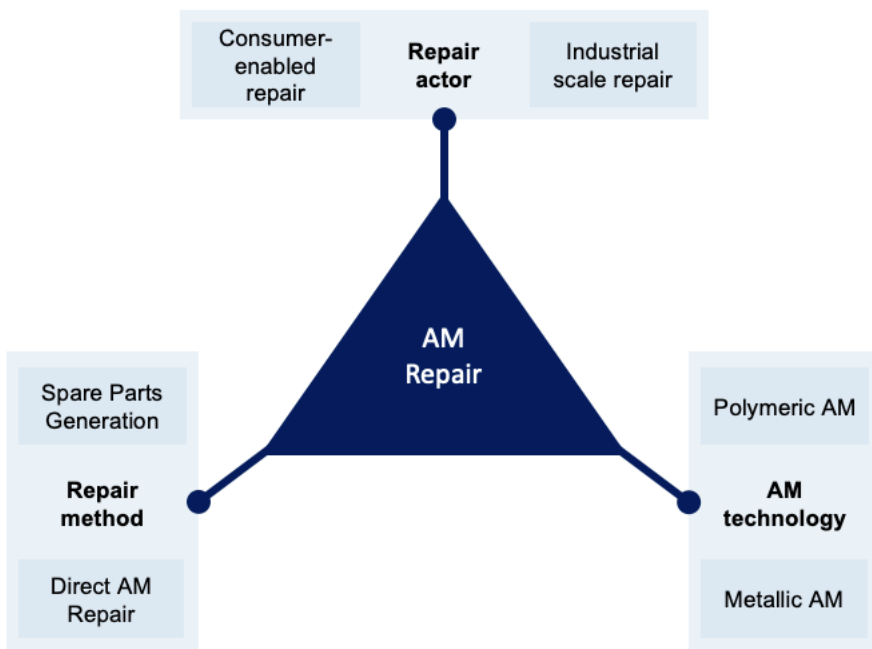


Figure 15: Differentiation of AM Repair classifications

Firstly, there needs to be a differentiation of two repair types: (A) spare part generation, and (B) direct part repair enabled by AM technology.

(A) Spare part generation aims at producing replacement parts for exchanges when a failure occurs in a system or a product.

(B) In contrast, direct repair is applied directly on the part and AM technology is brought into immediate proximity of the part defect.

Secondly, the interview partners described various application cases that can be clustered into two categories: (a) Consumer enablement, and (b) industrial scale repair applications.

(a) Utilization of decentral 3D printing facilities driven by consumer enablement to repair. Here, the consumer is actor for repair applications.

(b) Industrial scale application of repair deals with commercialization of repair as part of a company's business model.

Thirdly, there needs to be the common technology process differentiation between Polymeric AM (α) and Metallic AM (β).

(α) Polymers being printed in a layer-by-layer manufacturing process.

(β) Metal materials being printed in a layer-by-layer manufacturing process.

Repair Method		
	Spare Part Generation	Direct AM Repair
Definition	Printing spare parts to replace defective component to repair the system	Defective product/component is repaired by AM technology
Current status	Industry- and business case-specific application, but already being implemented with economic success	Rare industry- and business case-specific application; lighthouse projects recently launched
Examples	<ul style="list-style-type: none"> Defense (Temporary parts), Rail (Steam generator), Oil & Gas (Valves, pumps, heat exchangers) Repair cafes (Project Sharepair) 	<ul style="list-style-type: none"> Aviation (Turbine blades), Energy (Valves, pumps, heat exchangers, combustion parts/<u>burners</u>), Marine (Propellers)
Outlook	Growing market with positive business cases to be identified	Market potential and specific positive business cases to be recognized
Pros/Cons	+ Opportunity for rare or urgently needed spare parts	- End-to-end cost of manufacturing process
	+ Added value in time to market	- Certification and qualification processes
	+ Reducing stock (digital spare part inventory)	- Acceptance problem for printed part
	+ Mobile printing opportunity	- Material compatibility
		+ Material-efficient, more sustainable solution + Large automation potential (robotics) + Small energy and heat input into material + No disassembly needed - Cumbersome mechanical failure diagnostics - Limited non-destructive testing capabilities - Limited part accessibility; trajectory planning - Required material compatibility

Figure 16: Repair method comparison of Spare Part Generation and Direct AM Repair

Figure 16 provides a comparison of spare part generation and direct AM repair, defining the method activity, indicating the current status and examples, and providing an overview of the advantages and disadvantages mentioned in the interviews. It can be seen that the interviewees regard spare part generation as more developed and economically integrated, whereas direct AM repair is perceived as rare, but in some cases highly successful business case.

Direct repair is used for wear and tear parts facing high exposure. AM enables to these critical zones and extend the product life. Projects are in place, e.g., with the prominent EOS-Siemens collaboration on turbines. AM has proven to be useful not only for rapid prototyping but also for rapid repair of gas turbine burners. In Sweden, the burner is left intact and the upper 80 mm are turned off. Laser sintering technology utilized with Nickel-based super alloys enable the application of AM technology. That reduces repair times by the factor ten from 44 weeks to four weeks. Some interviewee voices mentioned that this concept is regarded as a lighthouse project to drive regionalization of production and spare parts on demand (EOS GmbH, 2021).

The interviewees added that in comparison to conventional (metallic) repair processes with large energy insertion into the part with unwanted implications on a part's mechanical properties and dimension, AM repair does not share these limitations. Furthermore, it was said that these repair processes would reduce the energy consumption for an economic and ecological benefit.

On the contrary, the trajectory planning for individualized repair cannot be performed manually. Thus, a higher degree of automation with digital process planning is required to scale up this solution. It was mentioned that scanning and surfacing needs to be integrated into Computer-Aided Manufacturing and making trajectory dependent on surface planes. It was added that for the current 3D-printing process, a plane is needed with a good accessibility and fit into printer is needed.

From the discussions and interviews it became apparent: The idea to create hybrid solutions for the best use case consisting of a process combination of subtractive normalization and then automated rebuild could leverage new possibilities of this technology towards repair.

Repair Technology			
		Polymeric AM	Metallic AM
Definition		Polymers being printed in a layer-by-layer manufacturing process	Metal materials being printed in a layer-by-layer manufacturing process
Application		Widely applied technology ranging from industrial to private use	Industrial use only due to high investment costs
Status - Repair		<ul style="list-style-type: none"> (Spare Parts): Consumer goods (e.g., coffee machine mechanical parts), Oil & Gas (Soft components) 	<ul style="list-style-type: none"> (Spare Parts): Defense (Temporary parts), Rail (steam generator), Oil & Gas (Valves, pumps, heat exchangers) (Direct Repair): Aviation (turbine blades), Energy (Valves, pumps, heat exchangers, combustion parts/<u>burners</u>), Marine (Propellers)
Outlook		Limited, specific repair cases will economically become more reasonable	With decreasing technology costs more applications will spread Metallic AM utilization for repair
Pros/Cons		+ Cheaper than metal printing; more printer capacity	+ High mechanical strengths, close to conventional products
		+ Democratization of Polymeric AM	+ High quality and tolerance
		+ Less post-processing	- Cumbersome post-processing
		+ Easier to qualify	- Limitations by material compatibility
		- Limited mechanical properties	- High initial investments; reduced printing capacity
		- Limited print accuracy / quality	- No freeform-design with powder bed technologies
		- Lack of business case to repair rather than rebuy	
		- Lack of lighthouse plastic repair applications	

Figure 17: Repair technology comparison of Polymeric AM and Metallic AM

Figure 17 provides a comparison of polymeric and metallic AM, defining the repair technology, indicating the current status and examples, and providing an overview of the advantages and disadvantages mentioned in the interviews. It can be seen that polymeric AM is present both in smaller, private settings as well as in industrial settings, whereas metallic AM is currently limited to industrial use. It was mentioned that for industrial high-performance parts, Metallic AM is more widely used. Even though polymeric AM enables a simple print upon surfaces, it has not been applied. Due to material properties and reduced mechanical strengths of plastics, tooling or critical

parts are primarily made from metal. The voices stated that the key to a higher integration of metallic AM would be the open-minded search for and identification of business cases.

Furthermore, interviewees mentioned that metal products have a higher repairability by applying welding technology. On the other hand, according to interview voices, plastics face limited repairability (e.g., Polyethylene terephthalate or PET) as in case of unsuitable material combinations the material's cohesivity and adhesivity would not support the combination of various layers. Economically, repair applications make sense when the value of a part increase the repair effort. According to interviewees, this is marginally the case which often results in the replacement of the entire plastic component or product system.

In summary, the voices indicated that polymeric AM is more advanced, given the consequence of democratization, simplicity and small cost of this technology, whereas metallic AM requires large initial investments and cumbersome post-processing. It was indicated, though, that metallic AM has a higher overall business application potential.

Repair Actor				
Repair Actor	Consumer-enabled repair		Industrial scale repair	
	Consumers		Manufacturing company (OEM, third party provider)	
Current status	Niche application enabled by democratization of AM technology		Industry- and business case-specific application	
Examples	<ul style="list-style-type: none">Repair cafes (Project Sharepair)Consumer goods & household productsSmall mechanical defects to be repaired using AM		<ul style="list-style-type: none">(Direct Repair): Aviation (Turbine blades), Energy (Valves, pumps, heat exchangers, <u>burners</u>), Marine (Propellers)(Spare Parts): Defense (Temporary parts), Rail (Steam generator), Oil & Gas (Valves, pumps, heat exchangers)	
Outlook	Expanding legislation ("Right to repair")		Growing market with positive business cases to be identified	
Pros/Cons	+ Decentralized repair	- Liability in case of failure	+ New repair business model opportunity	- Local expertise needed on site
	+ Reduction of stock for warranty spare parts	- Potential loss of quality and AM limitations	+ Potential: cost-effective spare part generation	- Cumbersome certification & qualification processes
	+ Business model opportunity	- Loss of after sales market	+ Optimization of logistics	
	+ Pressure by consumer	- AM knowledge needed		

Figure 18: Repair actor comparison of consumer-enabled repair and industrial scale repair

Figure 18 provides a comparison of consumer-enabled repair and industrial scale repair, defining the repair actor, indicating the current status and examples, and providing an overview of the advantages and disadvantages mentioned in the interviews. It can be seen that consumer-enabled repair is still a niche segment with potential depending on changing circumstances. These circumstances of change are described in chapter 3.1.3 Conditions for higher integration of AM Repair.

Repair cafés and the enablement of the consumer to repair, less an industrial approach. Consumer-enabled repair (e.g., privately at home or in repair cafés) needs to be separated from industrial

repair services. According to the interviewees, the repair potential for standards parts in consumer goods industry like coffee machines by utilizing AM is recognized as solid. Often those products remain fully functional aside from one small mechanical dysfunction. When warranty conditions are met, manufacturers do not repair those machines but send a new one. As repair is not envisaged by the original producer, a workaround for repair application has been developed for consumer-driven repair. Ongoing research projects linked to consumer-enablement like “Sharepair” (see 2.1.3 Existing AM repair applications), focus on polymeric AM and in particular the fused deposition modeling process. Limitations are seen in terms of part performance, e.g., high loads or temperature resistance, as polymeric AM faces inherent procedural technological boundaries, including the material performance. Particularly safety-related parts such (e.g., brakes) are mentioned to be an unsuitable application case. Furthermore, the accuracy of 3D printing might be insufficient to replicate the shape of a part (e.g., keyboard). Often the restrictive original part environment does not allow creative design solutions emerging from reversed engineering, as for example space between the parts is too small.

Furthermore, it was mentioned that the 3D printing process requires time and professional expertise, even more when applying reversed engineering techniques. In case of consumer-driven repair, designs or technical drawings are often not available or provided by the original manufacturer. Consequently, a redesign process featuring multiple iterations is required for a successful repair. Among the interviewees, 3D scanning technology is regarded as an innovative and yet limited tool in the redesign process. 3D scanning reproduces superficial design characteristics and cannot facilitate or simplify the functional analysis and subsequently functional redesign of a part to repair the original product. Problem: With necessity of AM production and a part which is not available – original part to reproduce might be too defective – expensive as iterations.

Industrial AM activities revolve around business model driven approaches with manufacturing companies at the center of the repair activity. According to the interviewees, AM provides strong advantages when integrated into regular company processes. Digitization and AM are closely connected. Digitized designs could enable fast operations and are the basis for further digital activities upstream.

3.1.1 Opportunities, barriers and cross-industry comparison of AM Repair

In this chapter, the opportunities, barriers and industry comparisons will be presented.

General opportunities and barriers

Based on the interview responses, clusters are formed to group the opportunities as well as the barriers of utilizing 3D printing for repair applications.

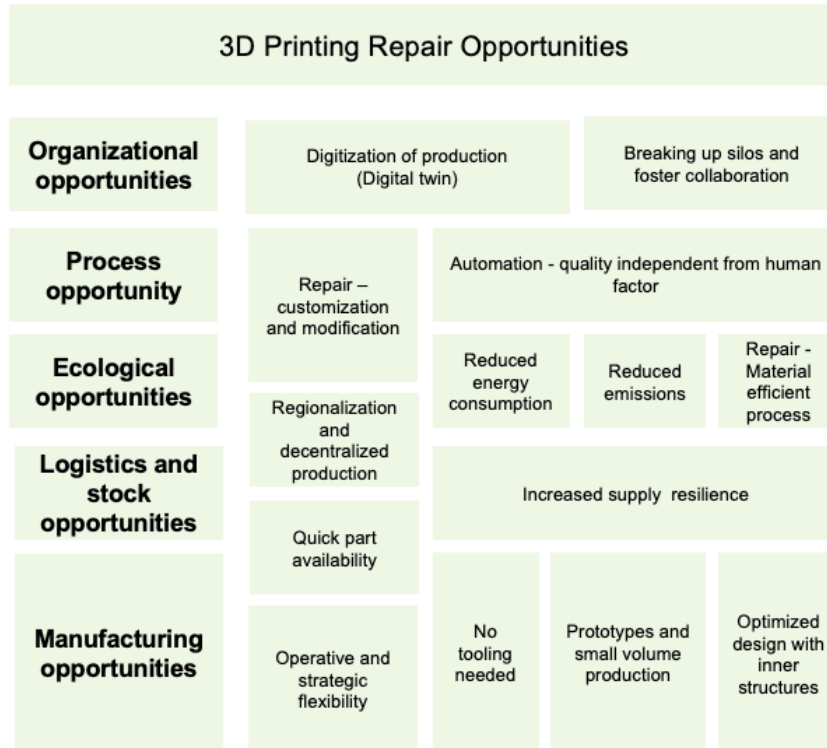


Figure 19: Opportunities of Additive Manufacturing Repair



Figure 20: Barriers of Additive Manufacturing Repair

Indicative potential evaluation for various industries

In this chapter, an overview of the potential across industries is given based on the interview voices. As described in the chapter 2.3 Interview, the results cannot be seen as scientific facts but as opinions and statements from various academic and industrial perspectives.

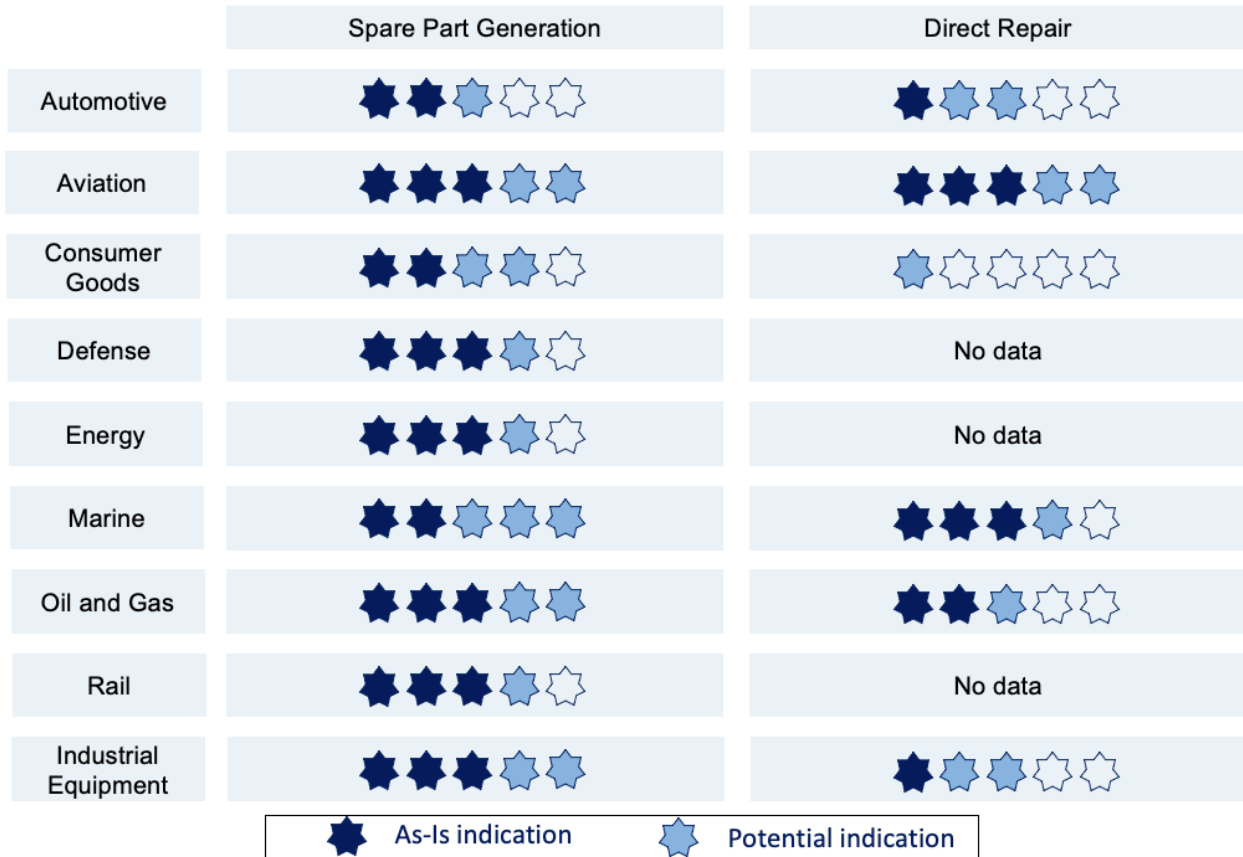


Figure 21: Industry comparison of AM Repair integration and potential

Figure 21 shows that particularly the aviation industry, the oil and gas industry, the industrial equipment industry and to some degree the marine industry are considered to have a high potential for AM spare part repair in parallel to being advanced in the integration of that technology. Based on the interview voices, direct repair suitability and potential particularly matches with aviation industry and marine industry.

In the following, the indicative degree of technology implementation and the potential of each industry is summarized by an individual figure, supported by a visualized pie chart.







		Spare Part Generation		Direct Repair	
Automotive	Already implemented		<ul style="list-style-type: none"> AM spare part production for industrial equipment, not in series Application for vintage car collectors via reverse engineering 		<ul style="list-style-type: none"> Tested but not implemented according to interviewees
	Current research		<ul style="list-style-type: none"> Customization, e.g., individual dashboards of premium products; e.g., gamification in China 		<ul style="list-style-type: none"> Currently tested and used for motorsport repair
	Projected future potential		<ul style="list-style-type: none"> Potential for spare parts on demand, and for rare spare part repairs in industrial equipment 		<ul style="list-style-type: none"> AM repair / part modification enabling customization Automation of direct repair processes

Figure 22: Industry comparison - Automotive







		Spare Part Generation		Direct Repair	
Aviation	Already implemented		<ul style="list-style-type: none"> Advantages in production lead time, cost of conventional production or original manufacturer supply limitations Cumbersome qualification processes 		<ul style="list-style-type: none"> Application - aircraft engines Product stewardship motivates to reduce downtime (GE/Rolls-Royce) Strict regulations and qualifications
	Current research		<ul style="list-style-type: none"> Development for AM for new aircraft programs Lightweight, optimized parts 		<ul style="list-style-type: none"> Ongoing identification of business cases
	Projected future potential		<ul style="list-style-type: none"> Scaling up of AM spare part repair Opportunity: CFRP repair solutions 		<ul style="list-style-type: none"> Potential AM repair / modification enabling customization Automation of direct repair processes

Figure 23: Industry comparison - Aviation

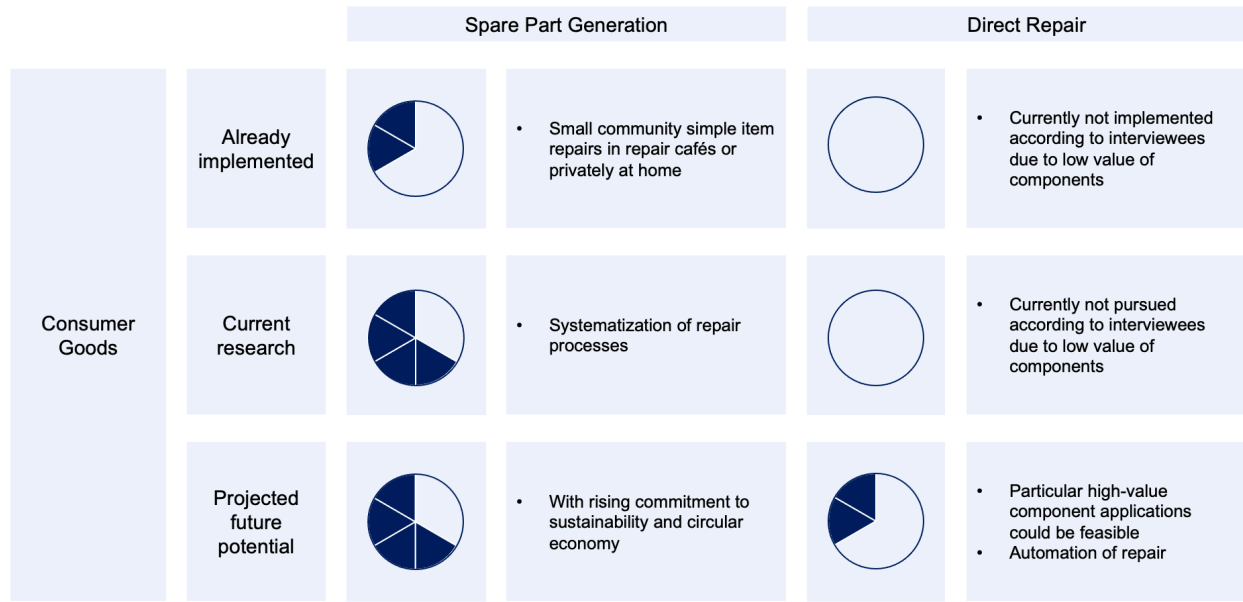


Figure 24: Industry comparison – Consumer goods

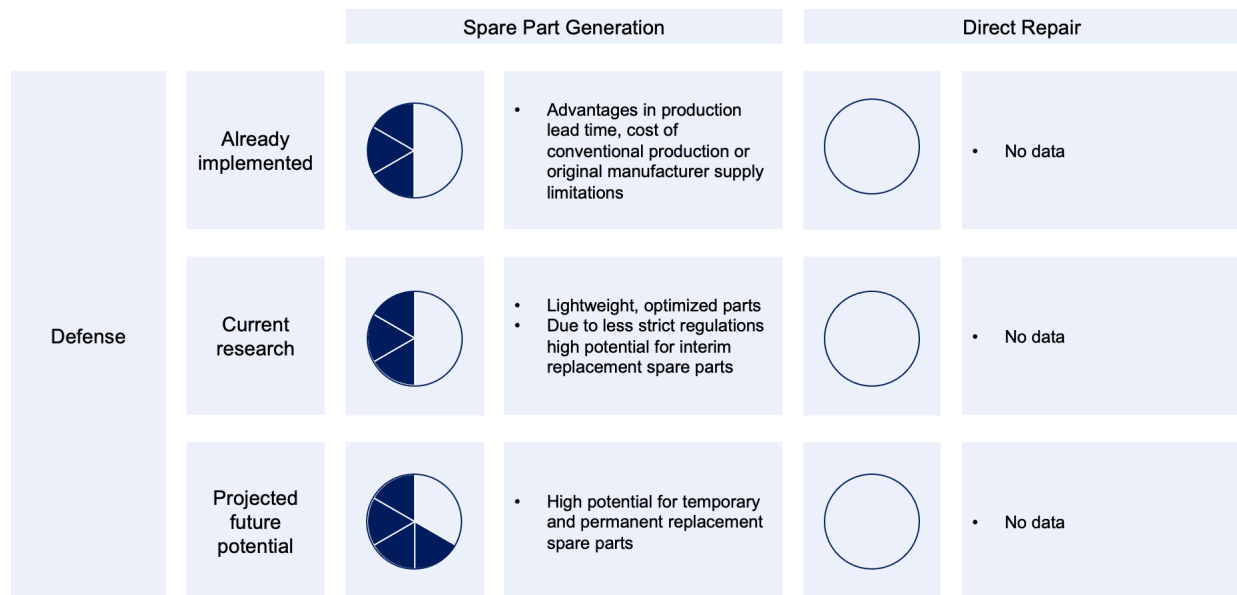


Figure 25: Industry comparison - Defense







		Spare Part Generation		Direct Repair	
Energy	Already implemented		<ul style="list-style-type: none"> Strong use cases for offshore wind energy and hydro energy generation 		<ul style="list-style-type: none"> No data
	Current research		<ul style="list-style-type: none"> Identification of further application fields 		<ul style="list-style-type: none"> No data
	Projected future potential		<ul style="list-style-type: none"> With growing spare part redesign catalogues, AM benefits increase Opportunity: Novel repair business models 		<ul style="list-style-type: none"> No data

Figure 26: Industry comparison - Energy







		Spare Part Generation		Direct Repair	
Marine	Already implemented		<ul style="list-style-type: none"> Ship diesel engine parts Outdated mechanical components 		<ul style="list-style-type: none"> Successful applications for ship propellers/impellers Laser deposition welding / cladding on ship hull
	Current research		<ul style="list-style-type: none"> Further identification of business cases 		<ul style="list-style-type: none"> Further identification of business cases
	Projected future potential		<ul style="list-style-type: none"> Increasing printing space for larger components 		<ul style="list-style-type: none"> Automation of direct repair processes

Figure 27: Industry comparison - Marine

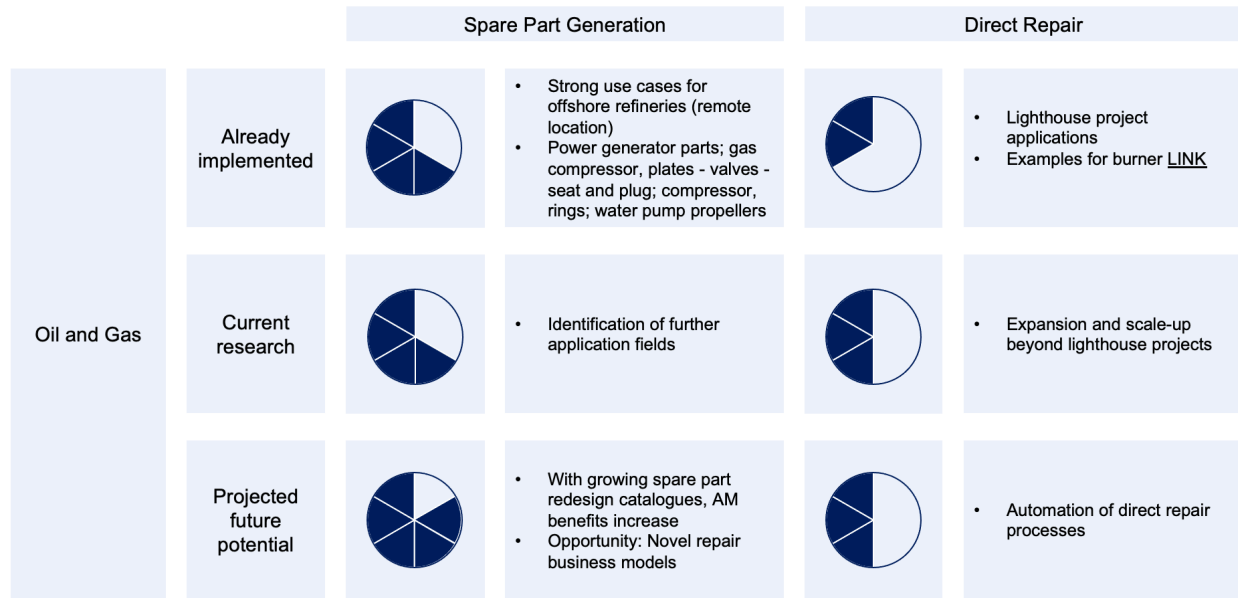


Figure 28: Industry comparison - Oil and gas

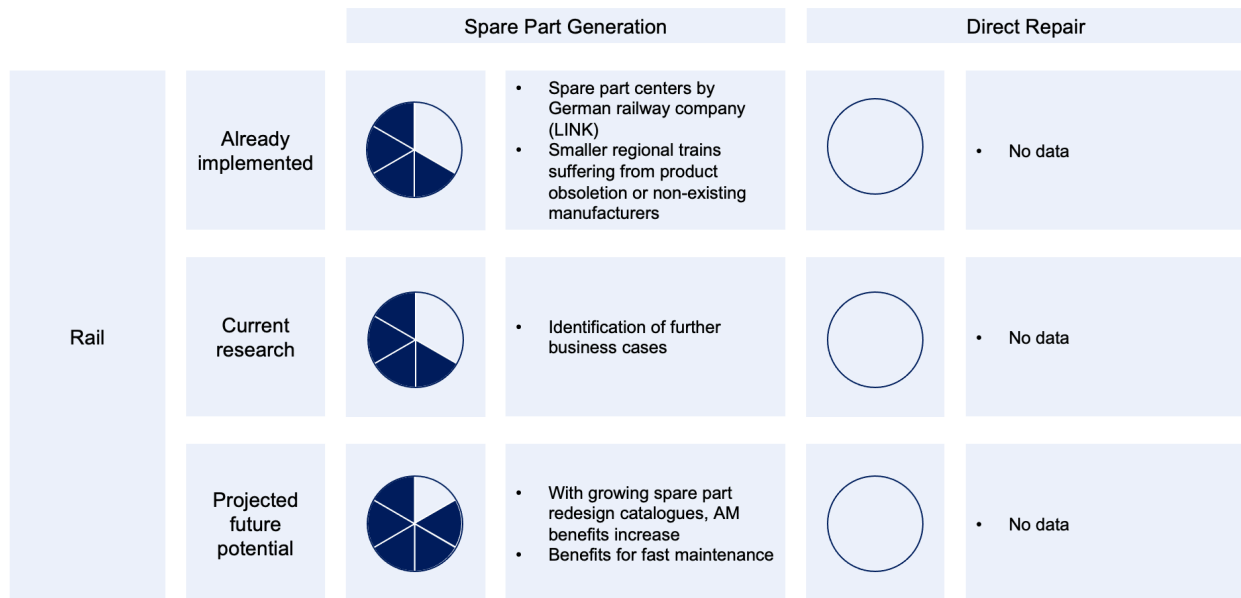


Figure 29: Industry comparison - Rail

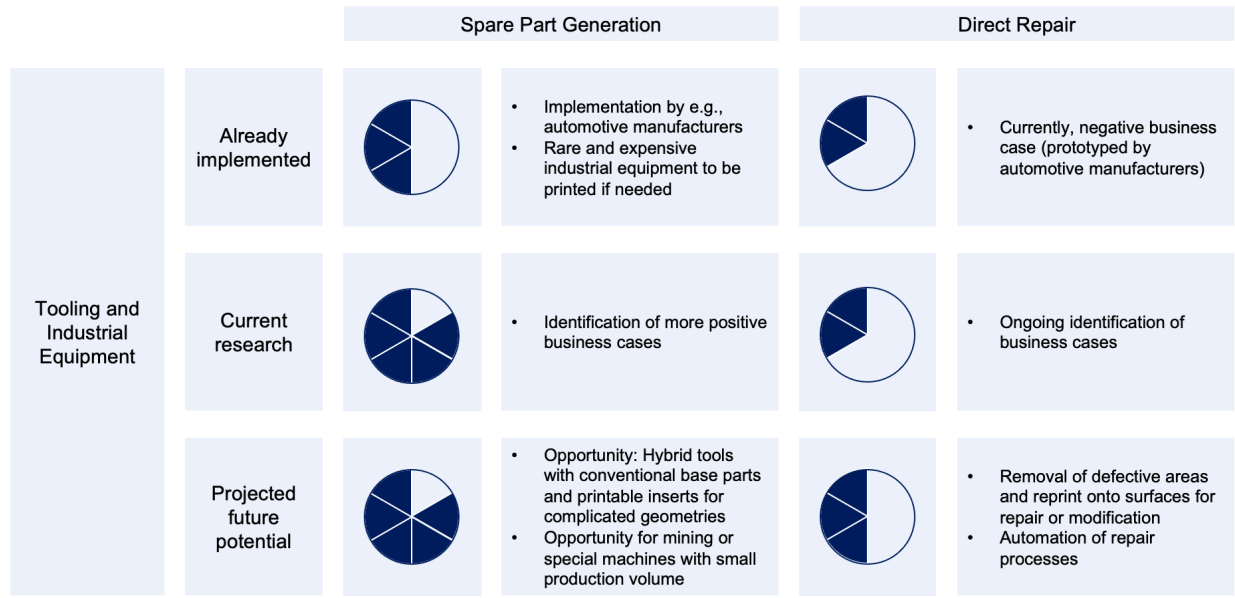


Figure 30: Industry comparison – Tooling and industrial equipment

3.1.2 AM Repair Assessment Framework

This AM Repair Assessment Framework serves as guideline for companies to understand relevant dimensions of AM in repair applications and evaluate their product portfolio accordingly. This framework is extracted from data gained from the interviews and needs to be acknowledged as indication. From the data, a minimum requirements list and assessment catalogue can be derived. It could help to understand the relationship between AM and Repair applications, serve as a guiding principle and orientation for companies, eventually becoming the foundation for maturity assessment of parts/products in regard to AM repairability.

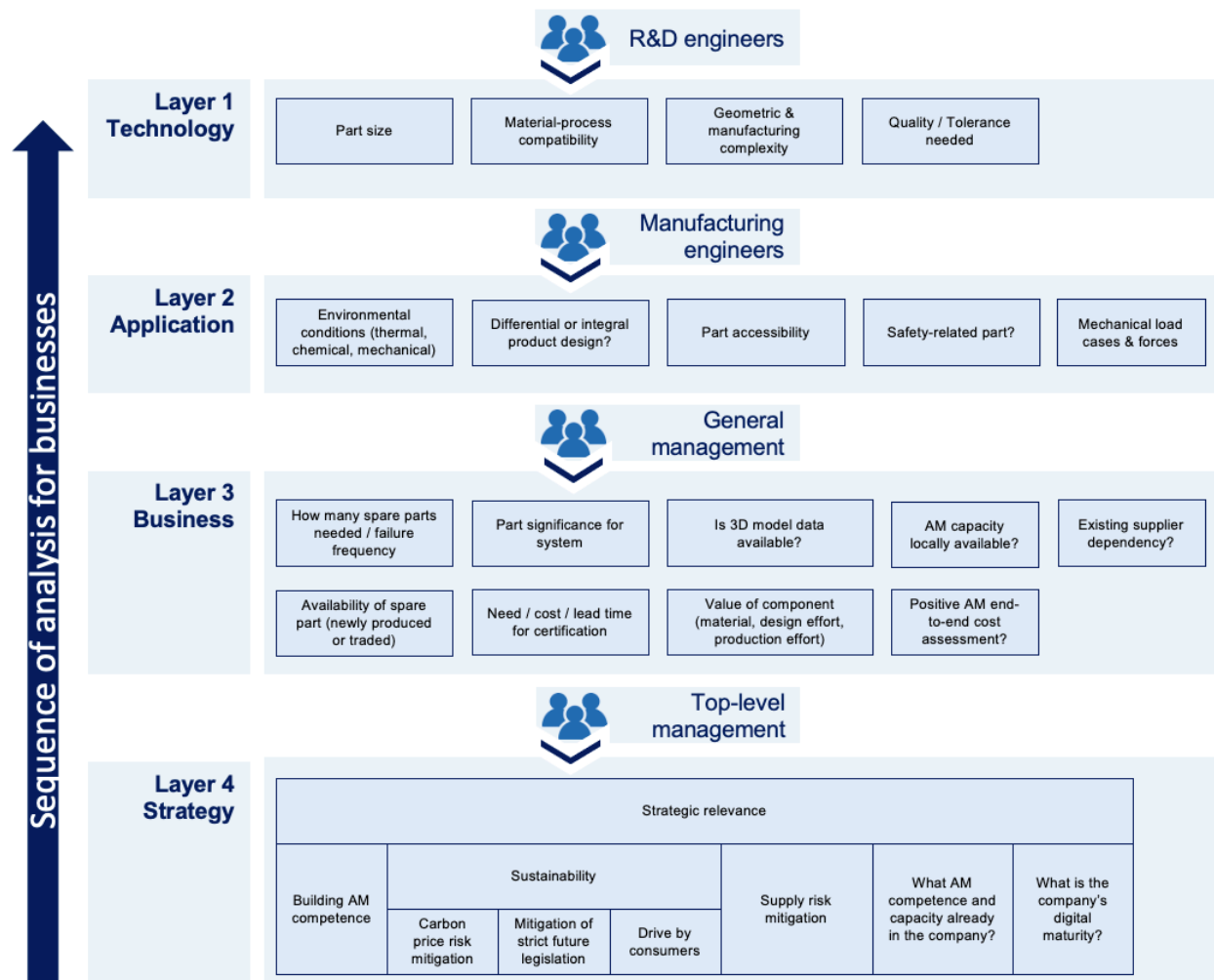


Figure 31: AM Repair suitability assessment dimensions

The Figure 31 shows the suitability assessment dimensions with regard to AM Repair activities. The sequence of analysis from business perspective is indicated by the arrow, from high-level strategy to concrete technology point of view. This summary of assessment dimensions (strategy, business, application and technology) does not represent the most efficient way to assess the repair potential of a part enabled by AM. This would mean to mix dimensions (primarily business and technology layers) that are in average the most decisive ones for the assessment and would require a deeper set of interviews. Rather it gives an understanding of the relevant clusters and their assessment dimensions for AM repair. Furthermore, it shows the involvement of different levels of stakeholders

Layer 1	Part size	Max. printing space
	Material-process compatibility	Compatible
	Geometric & manufacturing complexity	Complex*
	Quality / Tolerance needed	Low tolerances
Technology fit		
	Environmental conditions	Compatible
	Mechanical load cases & forces	Low
	Differential or integral product design	Differential – components
	Part accessibility	Direct
Application fit	Safety-related	No
Layer 3	How many spare parts needed / failure frequency	Small amount / small frequency
	Part significance for system	High significance / crucial
	Value of component (material, design effort, production effort)	High
	Is 3D model data available?	Yes
	Availability of conventional spare part (newly produced or traded)	No or unsuitable due to long lead time or production cost of conventional part
	Existing supplier dependency?	Yes
	AM capacity locally available?	Yes (inhouse or third-party)
	Need / cost / lead time for certification	No / low
	Positive AM end-to-end cost assessment?	Yes
Business fit		
Layer 4	Strategic decisions	
Strategic fit	Building AM competence	
	Pursuing sustainability	
	Supply risk mitigation	
	What AM competence and capacity already in the company?	
	What is the company's digital maturity?	

Figure 32: AM Repair suitability assessment framework model

The Figure 32 details the framework and adds a favorable quality of each dimension, based on the preliminary interview results and feedback interviews. By this indicative figure, companies can easily understand the dimensions and quickly check for the suitability of their parts and products.

3.1.3 Conditions for higher integration of AM Repair

This chapter summarizes the interview outcomes to the question of what conditional changes are needed for a higher integration of AM technology for repair applications. Based on the interview responses, clusters are formed to group the factors that impact the integration depth of AM repair in the future.

OEM / manufacturer mindset change	Recognize business opportunity in repair market / BM change	Provide access to original 3D models	Progress on Secured Distributed Manufacturing	Leverage and strengthen relationships between OEM and suppliers
Legislation	Increase legal and regulatory pressure towards sustainability	Press on "Right to repair"	Reform intellectual property right	Liability and responsibility for AM (repair) failures
		Press on CO2 price		
Visibility	Integrate AM repair solutions into manuals, guidelines and standards	Maintain communication about AM and upcoming opportunities	Promote regular process integration of AM	Promote lighthouse projects for repair applications
Leaner & streamlined qualification	Simplify and digitize qualification processes	Allow more creative repair solutions		
AM Manufacturing process improvements	Decrease post processing	Develop more materials	Increase compatibility of material	Reduce costs for material and printing
	Increase builder space / printing space	Simplify guidance to navigate through AM process settings	More intuitive industrial set-up of AM	Need for sustainability advantages in AM processes
Diagnostics technology	Develop technology and processes for failure diagnostics	Develop technology and processes to validate repair solution		
Automation	End-to-end digitization	Industrialize and automate printing process	Improve interface of robotic systems and AM	
Organizational change management	Identify opportunities for AM implementation	Integrate design for repair paradigm	Promote knowledge transfer and enablement of workers	Increase leadership support and trust
Education	Include AM into professional education	Integrate AM education into engineering courses		

Figure 33: Condition changes necessary for higher AM Repair integration

3.1.4 Community discussions of future AM Repair topics

Based on the literature study regarding ongoing future tech applications linked to AM repair, the interviewees were asked regarding the ongoing discussions in AM repair community as well as their assessment of three concrete future AM repair applications.



Figure 34: Word cloud – Future developments discussed in AM repair community

The Figure 34 shows the major future developments discussed in the AM repair community based on the interview responses. The points “decentralized repair” and “predictive maintenance” were mentioned by highest intensity, followed by “3D scanning and reversed engineering”, “AM waste recycling”, “sustainable 3D printing”, and “process automation and robotic repair”.

An in-detail analysis of these indications would exceed the scope of this thesis. Thus, it will remain an open point to continue research.

3.2 Consolidating summary

Based on the methodology of this work, a practical understanding of AM applications in industries, their opportunities, barriers and future potential could be provided.

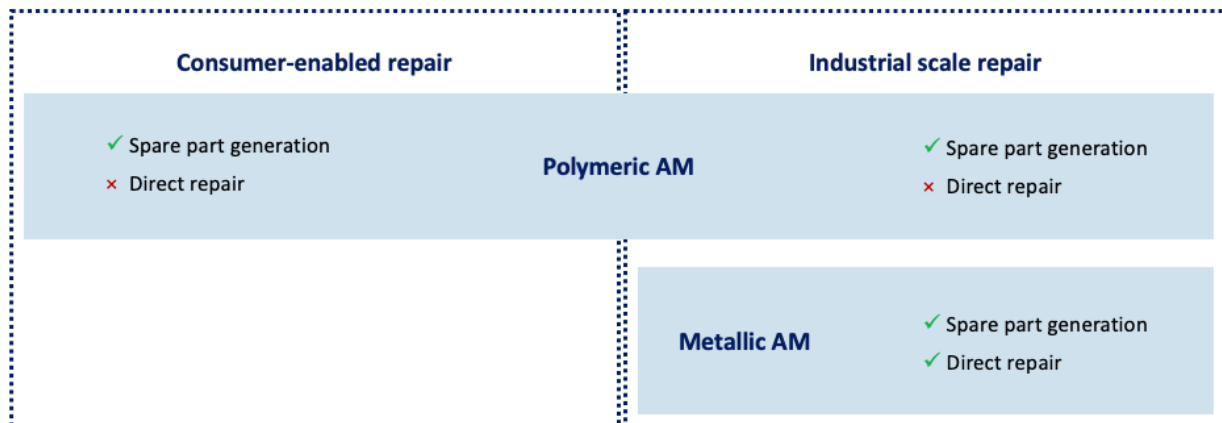


Figure 35: Matching of dimensions of AM Repair applications

As depicted in Figure 35, the insights into the industries indicated that consumer-enabled repair is currently only facilitated by Polymeric AM, providing spare parts. Direct repair is not performed due to the plastic material's low material value. Economically, it makes more sense to reproduce the entire part instead of performing direct repair. Furthermore, the utilized materials in direct repair need to be compatible in the way that their layers adhere to each other. Similar problems are faced by industrial scale direct repair with polymeric.

Beyond the status quo analysis, this thesis aimed at identifying opportunities and barriers for AM in repair. The prominent increase of significance of sustainability for consumers, politics and companies, might lead to the economic need to change to more circular business models. With the continuous rise of the carbon dioxide price for products – analyzed along the entire lifecycle perspective – minimizing the respective emissions might become a decisive factor of competitiveness. AM has already been discussed for many decades, but as reflected in the interviews, now this technology is more and more integrated into regular manufacturing processes and included into daily shopfloor activities of companies. For the particular case of repair applications, the evaluated potential can be summarized as high, but not for all applications. AM technology does not fit all business cases. With costs being the driving force, those positive business cases need to be identified and exploited. The point of flexible manufacturing was mentioned and emphasized during the course of interviews. AM allows to produce highly diverse parts and geometries without the need of tools. That, combined with the enablement of on-site and local production plays a crucial role for industries facing remoteness and inaccessibility for their operations. Still, even though printing parts is possible, it became clear that there needs to be a business case for a deep and true integration of AM in repair applications.

With increasing user and consumer responsibility and more sustainable products being demanded, repair initiatives enabled by AM could positively contribute towards an improved product longevity and eco-footprint. Despite often mentioned limitations, AM brings novel opportunities for product designers, engineers and managers to optimize their operations, maintenance and logistics, and by positively impact use of natural resources.

4. Discussion

The thesis results provide an understanding of current AM Repair application across industries and build the foundation for the development of an assessment framework for parts or products with regard to their AM repair suitability. In the subsequent chapters, the following points will be presented: firstly, the main contributions, secondly, the controversial issues, and, thirdly, the constraints.

4.1 Contribution of this work to research

The main contribution of this paper can be concluded as follows:

- Increased industry understanding of opportunities, barriers and current implementations of AM Repair technology;
- Input for decision-makers in industries, politics and academia regarding required the conditional changes to deepen the integration of repair applications enabled by AM;
- Identification of key characteristics that are decisive for AM repair suitability of parts and products;
- Development of framework foundations to evaluate the potential of parts and products for AM repair applications;
- Identification of prominent discussion topics in the community with regard to AM repair future applications.

4.2 Controversial issues

The subsequent overview will summarize the controversial issues that were covered during the interviews, and in particular how the voices differed in terms of their statements.

- General potential of AM repair applications
 - All interviewees identified the existing potential for 3D printing in repair applications but differed in terms of their optimism. The indications in this thesis need to be seen as averaged summary of those voices.
 - The industry stakeholders focused on opportunities and business applications of AM repair, whereas interviewees from academic background rather emphasized the technological limitations and presented their assessments regarding its opportunities with greater care.
- Metallic and polymeric direct repair potential
 - Some argued that due to the low cost of polymeric parts and products, this application field does not have a large development potential. Some proceed that under changed conditions, e.g., after the adaptation of repair business models in the

industry, polymeric or hybrid components of also higher value could be suitable for direct polymeric AM repair. Similarly, it was said that the integration of robotics and failure diagnostics into 3D printing could enable an automated, less human-factor dependent and less cumbersome repair process.

- Opportunities and barriers of AM repair
 - The interviewees agreed that AM repair applications have a high sustainability potential. Different reasons stated by various interviewees include a repair business model that might prolong the product life time, a potentially lower consumption of energy during the manufacturing process, and a potentially lower overall emission of carbon dioxide due to massively reduced logistics and storage needs.
 - A number of interviewees argued that the technical limitations in terms of material performance issues, the product quality process instability as well as the low surface quality have been overcome. When comparing this to other statements, though, it becomes clear that this assessment must be seen as contextual and dependent on the application case. Still, these process technology improvements broadened the range of viable applications. Similarly, the cost of investment for the printer and the supplement material has decreased, resulting in more economically viable applications.
- Industry potential
 - It has been noticed that the interviewees from various backgrounds selectively perceive AM repair applications based on their experience. Thus, the insight into different industries cannot be based on the majority of voices or cross-checked in the exploratory interview.
 - Furthermore, it needs to be highlighted that new application opportunities are continuously arising with AM technology which leads to a rapidly changing state of the art.
- Proposed changes of conditions to strengthen AM repair applications
 - During the interviews, the interviewees mentioned a broad range of changes that could leverage the potential of AM repair. Whereas the academic perspective highlights process and technology factors, the industrial business side emphasizes challenges in the complexity and costs of qualification processes. Furthermore, the 3D printing service providers argue that the cumbersome reversed engineering processes together with the mindset of original manufacturers in terms of accepting repair business models and providing access to 3D models are levers for increasingly utilize AM for repair. This diversity of input results in a complimented overall set of proposals.
- Identification of decisive factors for AM repair suitability

- Some interviewees argue that cheap, basic components are more suitable for AM repair due to their design simplicity and high waste rate that is linked to their low value. Contrarily, others say that high-value products could be best used for AM repair as their economic value drives ambitions for prolonging their functional life time. Based on that controversy, the availability of 3D data appears to be decisive for the one or the other point of view:
 - Without the data, it requires time and expertise to redesign the part with similar functionality – if even possible. Thus, simple part geometries simplify that process.
 - With existing data, AM offers unique opportunities in terms of printing complex structures.
- On the one hand, some interviewees explain that parts and products with a high failure rate are better candidates for an AM repair due to their probability of a technical failure. On the other hand, some argue that low failure rates would do so, e.g., for rarely needed industrial equipment. By that, logistics and storage costs and efforts could be saved by printing the spare parts on demand. Furthermore, they say, that from the economic point of view, AM is not suitable for a mass production of spare parts.

4.3 Methodological constraints

The methodological constraints of this work need to be highlighted:

- Literature Review
 - Due to time constraints, the focus of this work is on the interviews rather than the conduction of a detailed literature review.
- Data Analysis
 - The data from the European Commission follows a standardized format but has not been reported by all countries on a continuous basis from the beginning. This fact hinders the interpretation of the analysis.
- Interviews
 - The number of 17 interviewees is limited and can only provide a selective view on the subject of AM for repair applications. Also, the selection of interview candidates might have scoped and shaped the results.
 - Given the diversity of professional backgrounds of the interviewees and the limited sample size, a comparison of voices with regard to a similar concrete application was not possible for all content clusters and subjects.

- The nature of exploratory interviews with a questionnaire of qualitative questions highlights the subjectivity of the results.
- There has been a potential loss of information between the sender (interviewee) and the recipient (interviewer) or a misunderstanding by the recipient.
 - Due to the potential illusion of a homogenic dialogue based on common definitions and terminology, there has been a potential misunderstanding, particularly of prominent or even “hyped” technological developments.
- A thorough validation of preliminary interview results by feedback interviews was limited due to time and response constraints to seven feedback calls.

Due to these points described above, the results must be seen as indicative and require further validation.

4.4 Recommendations and future work

This thesis is limited in its methodology and scope. As it only provides indications and excludes industries and research fields, it is recommended that future work investigates the following aspects:

- General recommendations
 - Validation of results with a larger sample size and with actors specifically working in the analyzed industries.
- Barriers and opportunities of AM repair
 - Deeper investigation of the identified barriers including mitigation possibilities
 - Deeper investigation of opportunities and practical leverage possibilities
- Industry application and potential comparison
 - Refinement of results and validation with stakeholders from the industry
 - Investigate and leverage on potential and lighthouse projects
- Proposed changes of conditions
 - Validation of proposed changes
 - Investigation of how those levers can be activated
- Framework
 - Refinement of framework on a theoretical basis by validating with a larger sample size and continuously update
 - Development of an organizational readiness assessment, also including the organizational needs for a successful AM implementation
 - Refinement in practice by working with real scenarios

- Automation of framework by a program to simplify and algorithmize the questions to ask
- Future of AM Repair applications
 - Investigation of the potential of the mentioned future technologies and application fields for AM repair and whether they could fundamentally change the integration of AM technology in repair processes

5. Conclusions

This thesis contributes to the research field by providing a bridge between the academic and the industrial ecosystem. Furthermore, it facilitates a practical understanding of current opportunities and barriers of AM technology for repair applications, combined with an industry overview and the foundations of a practical framework to evaluate the part or product potential for AM repair. This AM Repair Assessment Framework serves as guideline for companies to understand relevant dimensions of AM in repair applications and evaluate their product portfolio accordingly. Lastly, the current topics are gathered and summarized that are discussed in the community with regard to the future AM-enabled repair.

Based on the gathered and analyzed data, the formulated research questions are answered:

(1) What minimum set of opportunities and barriers does exist for AM repair technology?

The main opportunities are clustered in the dimensions as follows:

- Organizational opportunities;
- Process opportunities;
- Ecological opportunities;
- Logistics and stock opportunities;
- Manufacturing opportunities.

On the other side, the main barriers are equally clustered in the following:

- Organizational barriers;
- Process barriers;
- Legal barriers;
- Cost barriers;
- Manufacturing barriers.

Beyond that, also some industries that are relevant to the scope of this thesis were analyzed in regard to their status quo and their potential of AM repair applications.

(2) What indicators could be used by companies to evaluate their product portfolio for AM repair?

Based on the interview results, the following main indicators were identified:

- Technology fit
 - Part size

- Material-process compatibility
 - Geometric and manufacturing complexity
 - Printability of required tolerance or quality
- Application fit
 - Environmental conditions
 - Mechanical load cases and forces
 - Differential or integral product design
 - Part accessibility
 - Safety-criticality of part/product
- Business fit
 - Number of spare parts/repairs needed/expected
 - Part significance for the system
 - Value of component
 - Availability of 3D model
 - Availability of conventional spare part
 - Existing supplier dependency
 - Availability of local AM capacity
 - Need for certification activities
 - End-to-end cost transparency
- Strategic fit
 - Building AM competence
 - Existing AM competence
 - Pursuing sustainability
 - Pursuing supply risk mitigation
 - Analysis of digital maturity of company

(3) What is the minimum set of requirements for a more successful application of AM as repair method?

The required changes of conditions categories that were identified in the course of the thesis are:

- OEM/manufacturer mindset change;
- Legislation;
- Visibility;
- Leaner and streamlined qualification;
- AM process improvements;
- Advances in diagnostics technology;

- Advances in automation technology;
- Organizational change management;
- Education.

(4) What emerging AM tech repair applications are currently discussed in the community?

The following emerging tech repair applications are currently discussed in the community, with decreasing intensity in the list:

- Predictive maintenance;
- Decentralized repair;
- 3D scanning and reversed engineering;
- AM waste recycling;
- Sustainable 3D printing;
- Process automation and robotic repair;
- Large 3D printers;
- Miniaturization of parts;
- Printing electronics;
- 3D printer availability;
- Crowd-sourcing/platform design;
- Fiber-reinforced 3D printing;
- Condition-based monitoring;
- 4D printing.

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7. Appendix

Appendix 1: Master Thesis Data Privacy Notice

Confidential

Master Thesis – Repair Potential of 3D Printing interview DATA PRIVACY NOTICE

You have been selected to participate in the “Master Thesis – Repair Potential of 3D Printing” interview. The interview is being used for Nico Albrecht to extend theoretical research on product repairability enabled by Additive Manufacturing, bridging the gap between academia and industry.

The interview takes about 20 minutes to complete. It is important that you respond candidly throughout this interview, so we can get accurate results.

Participation in this interview is optional and entirely voluntary (there are no individual consequences if you choose not to respond).

Only the interviewer knows who the counterpart for the interview was. The results of this interview are anonymous. The anonymized data will be reviewed, analysed and processed by Bernd Peukert, the thesis supervisor of KTH Royal Institute of Technology.

Nico Albrecht who has access to your individual interview responses or are involved in creating reports/data analysis will be subject to strict confidentiality obligations in relation to access and use of the data and will be given adequate training on how to handle the data confidentially.

This interview is being administered by Nico Albrecht who is data controller for this interview. More information about how Accenture will process your personal data can be found in [Accenture Global Data Privacy Statement](#) placed on Accenture internal website and [Accenture’s Global Data Privacy Policy 0090](#).

All identifiable responses (incl. recordings) to the interview will be stored by Nico Albrecht and Accenture on an Accenture Laptop including MS Teams protected by a password for starting the Laptop and stored in a password restricted folder for a reasonable time to fulfil the above-mentioned purposes of extending theoretical research on product repairability enabled by Additive Manufacturing, bridging the gap between academia and industry, and in accordance with internal Accenture retention policies, (the maximum time such identifiable responses may be stored by Nico Albrecht is 6 months after which the data will be deleted, destroyed or otherwise rendered unidentifiable).

[Accenture’s Global Data Privacy Policy 0090](#) and [Accenture Global Data Privacy Statement](#) / [Accenture Global Data Privacy Statement](#) explains your rights, to inquire about access and rectify or reassure of your data or restriction of processing and object to its processing as well as the right to data portability in accordance with applicable data privacy laws. You can do this through [Data Privacy Tool](#) or by contacting Global Data Privacy Team: DataPrivacy@accenture.com or the Data Protection Officer at dataprivacyofficer@accenture.com, your employer directly.

Appendix 2: Catalogue of guiding questions for the exploratory interview series

#	Content Cluster	Question
	0	Self-assessment: Depth of knowledge regarding AM and repair?
	0	Self-assessment: What product industry are you familiar with?
1	1	How do you assess the general potential of AM for repair?
2	1	What opportunities and what barriers do you see for AM in repair?
3	1	What are the current capabilities of polymeric and metallic AM for repair applications – in comparison?
4	1	What are the current AM repair capabilities for AM parts and non-AM parts – in comparison?
5	2	When and under what prerequisites could AM utilization in repair be feasible and applicable in the future?
6	2	What kind of product type would be suitable for AM repair?
7	2	What industries might be suitable for product repair enabled by AM?
8	3	What product/part characteristics are needed for AM to be applicable as repair technology?
9	3	What (sequential) process steps are necessary to be taken when assessing repair potential of parts? What KPI could be suitable?
10	4	What future emerging tech applications utilizing AM repair do you regard as promising?
11	4	How do you rate the three emerging tech AM repair solutions? 1. Autonomous repair – “Self-maintaining city” 2. Sensors in AM products for repair and maintenance 3. 3D printing in deep-water/space repair applications

Legend of Content Cluster:

0: Self-Assessment

1: General AM repairability potential & barrier assessment

2: Repair scenario assessment for products and industries - AM, and non-AM parts

- 3: Requirements, characteristics, and potential assessment for parts
- 4: Emerging tech and future AM repairability solutions

