UNIVERSITY OF ICELAND

M.S. Thesis

in Industrial Engineering

Digital Transformation in the Aluminum Industry

From an Innovation Ecosystem perspective

Arnar Guðnason

February 2023

FACULTY OF INDUSTRIAL ENGINEERING, MECHANICAL ENGINEERING AND COMPUTER SCIENCE

Digital Transformation in the Aluminum Industry

Arnar Guðnason

Dissertation submitted in partial fulfillment of a
Magister Scientiarum degree in Industrial Engineering

Advisor
Rögnvaldur Jóhann Sæmundsson

Examiner
Marina Candi

Faculty of Industrial Engineering, Mechanical Engineering and Computer Science
School of Engineering and Natural Sciences
University of Iceland

Reykjavik, February 2023

Digital Transformation in the Aluminum Industry
From an Innovation Ecosystem perspective
Dissertation submitted in partial fulfillment of a *M.S. degree* in Industrial Engineering

Faculty of Industrial Engineering, Mechanical Engineering and Computer Science
School of Engineering and Natural Sciences
University of Iceland
Dunhaga 5
107 Reykjavik
Iceland

Telephone: 525 4000

Bibliographic information:
Arnar Guðnason, 2023, *Digital Transformation in the Aluminum Industry*, M.S. thesis,
Faculty of Industrial Engineering, Mechanical Engineering and Computer Science,
University of Iceland, 45 pp.

Abstract

The aluminum production industry is a significant contributor to global greenhouse gas emissions and electricity consumption. Digital transformation, and the adoption of Industry 4.0 technologies, has the potential to improve efficiency and sustainability in the industry. Innovation ecosystem, which is a network of actors that support innovation and knowledge creation, play a crucial role in the development and adoption of digital transformation in the aluminum industry. These ecosystems involve a diverse range of actors, including aluminum producers, suppliers, research centers, universities, aluminum clusters, and public bodies. Each of these actors has a unique role to play in the innovation process, and effective collaboration and cooperation between them is necessary for the successful implementation of digital transformation projects. Future research should focus on understanding the specific challenges and opportunities faced by these actors in the aluminum industry and how they can work together to drive innovation and sustainability.

Keywords: Innovation, Product Development, Innovation Ecosystem, Aluminum Production, Industry 4.0, Digital Transformation.

Útdráttur

Álframleiðsla ber ábyrgð á stórum hluta af losun gróðuhúsaloftegunda og notkun raforku á heimsvísu. Stafræn umbreyting og innleiðing Industry 4.0 lausna getur haft jákvæð áhrifa á nýtni og sjálfbærni í iðnaðinum. Vistkerfi nýsköpunar (e. innovation ecosystem) er net þátttakenda (e. actors) sem styðja við nýsköpun og miðlun þekkingar, leika lykilhlutverk við þróun og stafræna umbreytingu í áliðnaðinum. Þessi vistkerfi innihalda fjölbreytta þátttakendur, þar á meðal álframleiðendur, byrgja, rannsóknarsetur og háskóla, ál-klasa og opinbera aðila. Hver þessara þátttakenda hefur sérstætt hlutverk í nýsköpunarferlinu, áhrifaríkt samstarf og stuðningur milli þeirra er nauðsynlegur til að ná árangri í stafrænum umbreytingaverkefnum. Frekari rannsóknir ættu að einblína á að auka skilning á sérstökum áskorunum og tækifærum sem þessir þátttakendur standa frammi fyrir og hvernig þeir geta unnið saman til að keyra áfram nýsköpun og sjálfbærni.

Lykilorð: Nýsköpun, Vöruþróun, Nýsköpunarvistkerfi, Ál-framleiðsla, Fjórða Iðnbyltingin, Stafræn Umbreyting.

I dedicate this thesis to my partner, Kristín, the primus motor behind my studies.

Table of Contents

List of Figures

List of Tables

Abbreviations

- APS-A – Aluminum Production Supplier A
- AI – Artificial Intelligence
- CapEx – Capital Expenditure
- IIoT – Industrial Internet of Things
- I4.0 – Industry 4.0
- NAC-A – National Aluminum Cluster A
- OpEx – Operational Expenditure
- PAS-A – Primary Aluminum Smelter A
- PAS-B – Primary Aluminum Smelter B
- RF-A – Research Facility A
- RF-B – Research Facility B
- R&D – Research and Development
- SAP – Secondary Aluminum Production
- SAP-A – Secondary Aluminum Producer A
- TA – Thematic Analysis

Acknowledgements

I would like to start by thanking my family members for support and encouragement through both this master's thesis and my studies, my partner Kristín can't be thanked enough. I want to thank my colleagues at DTE who aided me at any point when needed. Especially my current supervisor Diego Areces for providing a flexible work schedule and always encouraging me, throughout my career and studies. Thanks to my executive coach Sandra Sif for assisting me with developing a roadmap and setting expectations for my research. Gratitude to all the individuals that agreed to let me interview them for this research, without them this thesis would not have been possible. Finally, I want to express my gratitude to my thesis advisor, Rögnvaldur Jóhann Sæmundsson, for his critique and guidance, which proved invaluable all through this research.

1 Introduction

1.1 Background

Aluminum is the second most produced metal, only surpassed by steel for modern societies. It has experienced significantly increased demand for it in the transportation, building, packaging and electrical engineering industries in recent decades (Guo et al., 2019). There were roughly 67 million metric tons of aluminum produced in electrolytic pots worldwide in 2021 (Aluminum, 2022). A continuous annual increase of 2.65% is predicted until the year 2029 resulting in a predicted yearly production of 78.4 million metric tons of aluminum by 2029 (Arnoldi, 2020). The aluminum production sector is one of the most energy intensive industries in modern times and has a serious impact on the environment. Approximately 1% of the global greenhouse gas emissions can be attributed to primary aluminum production (Paraskevas et al., 2016), and 4% of the worlds electricity is consumed by the primary aluminum industry (Sgouridis et al., 2021).

A precursor to aluminum smelting is the Bayer process. The Bayer process involves mining bauxite, a sedimentary rock and refining it into smelting grade alumina (Al_2O_3) (Marciano et al., 2006). In primary aluminum smelters, alumina is dissolved in molten cryolite in electrolyte pots and current passed through the solution. The carbon atom separate from the alumina and bond to the carbon that is present in the anode, leaving the molten aluminum at the bottom of the pot (Association, 2021). In modern aluminum smelters, the pre-baked anodes are systematically changed by operators using overhead cranes as they are consumed by the reduction process (Kvande & Drabløs, 2014). An operator siphons the liquid aluminum from the pots to a large crucible that is then transferred to a casthouse with a vehicle (RioTinto, n.d.-a).

In the casthouse the aluminum is handled, alloying elements are mixed with the aluminum and the aluminum alloy is casted into products that are then sold to customers for further processing (RioTinto, n.d.-a). Primary aluminum production is a complicated and uninterrupted process, operating in a closed loop. Modifications made early in the production process might affect processes in later production stages, thus hindering the possibilities aluminum smelters have for experiments to improve production (Souza et al., 2019). An overview of the main processes in aluminum smelters can be found below in Figure 1.

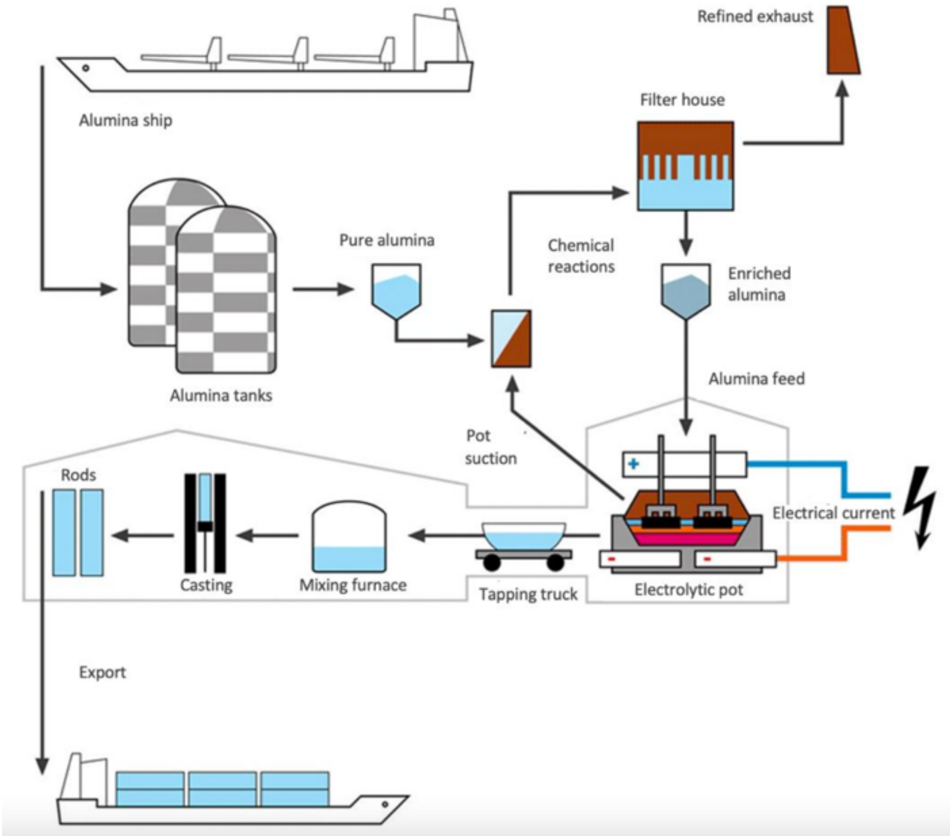

Figure 1: Aluminum Smelter Production Process (RioTinto, n.d.-b)

The production process differs in secondary aluminum factories. Instead of producing aluminum in electrolyte pots, recycled aluminum is collected, shredded and de-coated to remove contaminants from the surface. The shredded aluminum is then remelted and handled before being casted into products in the same way as in primary aluminum smelters (Aluminum, n.d.). Secondary aluminum production (SAP) is vital for the preservation of the environment. It requires less energy and produces less gas emissions than primary smelting production of aluminum. It also has the indirect effect of less bauxite mining and less alumina consumption due to less primary aluminum being used in production of aluminum products (Padamata et al., 2021). The SAP is a growing industry, and the European Aluminum Association has predicted that post-consumer aluminum available for recyclers could more than double by 2050 from 3.8 million tons per year to 8.6 million tons per year in Europe and the SAP industry is predicted to be responsible for more than 50% of total aluminum produced in a year across the world (Padamata et al., 2021).

DTE is an innovation startup company that recently has started to manufacture and sell devices and solutions for the aluminum industry after years of development. DTE has developed a first in industry elemental analyzer that is able to analyze chemical composition of molten aluminum in real-time using liquid-phase laser induced breakdown spectroscopy (LP-LIBS) technology (DTE, 2021a). This new technology replaces current manual and time-consuming methods to analyze chemical composition of aluminum which requires casting of a solid sample while DTE's solution can measure directly from the molten metal (DTE, 2021b). DTE's solution, named IREAS, consists of the elemental analyzers and an artificial intelligence-based cloud platform (DTE, 2021c). The near real-time analysis coupled with the predictive maintenance analysis software has positive outcomes for aluminum smelters potrooms. The in-situ application of the analyzers in aluminum production casthouses provide a platform for optimization of the casting processes currently utilized by aluminum casthouses. The analyzers also provide secondary aluminum producers with opportunities to improve their scrap usage and lower their operational expenditure (OpEx). The unprecedented knowledge of metal composition throughout the whole aluminum production process provide aluminum producers with quality control that has not been achievable before in the aluminum industry (DTE, 2021d). IREAS supports factories to improve production planning, reduce emissions, reduce waste, and contribute to increased sustainability and safety (DTE, 2021c).

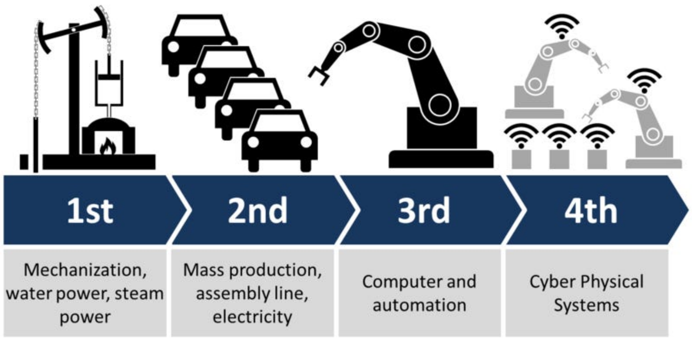

Figure 2: Industrial Revolutions (Roser, 2017)

Digital transformation is a new trend in manufacturing that enables the fusion of digital technology with conventional manufacturing. A series of rapid transformations denoting a leap in production methods due to the involvement of cyber-physical systems, the Internet of things, the Internet of services and, the smart factory format (Benitez et al., 2020). The term Industry 4.0 (I4.0) is becoming internationally accepted as a synonym for the digitization of industries, joining production with modern information and communication technology (Schoning, 2018). I4.0 platform technologies, including industrial Internet of things (IIoT), digital-twin (DT), artificial intelligence (AI), machine learning, cloud computing, etc., are providing additional opportunities for the aluminum production industry (Benitez et al., 2020; Gupta & Basu, 2019). Cyber-Physical Systems in general, refer to systems that gather, store, analyze and process data with IIoT, integrating the real physical and virtual world, including human machine interactions (Ralph & Stockinger, 2020).

The concept of innovation ecosystem has become popular the last 15 years, with rapidly growing literature (usually focusing on business and strategy) (Granstrand & Holgersson, 2020). Innovation ecosystem can be defined as a collection of institutions and organizations, the interactions and link between them, that supports innovation development and knowledge creation. The basis of that being that value cannot be created by a stand-alone firm and that contributions from a vast set of diverse actors is needed, including firms, universities, research centers, regulators and government bodies (Benitez et al., 2020; Matt et al., 2021).

1.2 Purpose

The purpose of this research project is to explore the digital transformation that is happening in the aluminum industry and the effect they have. Examine and find the different actors that exist in the field of aluminum production and discover their involvements in product development and innovation. This analysis will be conducted with the innovation ecosystem perspective.

This will aid DTE in creating and supporting their innovation ecosystem that surrounds their devices and technology. The company's technologies disruptive nature has resulted in setbacks in adaptation with current and potential customers. Thus, creating the appropriate conditions for innovation within DTE, with their customers, suppliers, and collaborators is vital. This will help DTE become a major supplier for the aluminum industry, whether that be primary aluminum production, SAP, or end-product production.

To improve the chances of DTE's technology's success, there is further innovation needed. Not only on the technology itself but multiple actors are required to act for value creation to happen for all stakeholders. Therefor this research project aims to discover the actors in the aluminum industries with the innovation ecosystem perspective, helping DTE defining a strategy that further enables innovation in the aluminum industry. Understand the roles and actions of these different actors, along with identifying actions that foster the adaptation of transformative technology. DTE's involvement in the aluminum industry is connected to the fourth industrial revolution, using vast amount of data, AI and IIoT for its solution. To reach the research purpose, the two research questions are: **How are actors of the aluminum industry driving the digital transformation in the industry,** and **how is digital transformation affecting manufacturing processes in the aluminum industry?**

1.3 Thesis Overview

The thesis structure is the following way, after this brief introductory chapter that introduces aluminum production, digital transformation, along with innovation ecosystem there is a literature review chapter. The chapter contains review on digital transformation, I4.0, and innovation ecosystem. In chapter three, the methodology used in this research is outlined, along with the data used in this research explained. Chapter four contains the results of the data analysis. Followed by a discussions chapter that gathers the key findings. Last chapter of the thesis is conclusions, providing a summary of the thesis.

2 Literature Review

2.1 Digital Transformation

Digital transformation is defined as process used to exploit digital technologies and opportunities to re-constructure economies, institutions, and society at the system level. For companies, it is the action of applying digital technologies in order to create value for the company (Matarazzo et al., 2021), changing the way companies conduct business, create relationships with customers, suppliers, and other stakeholders (Magistretti et al., 2021; Matarazzo et al., 2021).

Clear advancements in manufacturing, its output and processes can be contributed to the digital transformation along with the cultivation of business model innovation and customer value creation. A properly integrated digital transformation can boost the completive advantage of all stakeholders (Rocha et al., 2019). The success of digital technologies depends on how leaders and managers orchestrate the transformation, and the preparation of people using the products and services (Rocha et al., 2019). Digital transformation can be found everywhere, no business, industry or organization is unaffected by it (Brunetti et al., 2020).

2.2 Industry 4.0

The concept of a "Smart Factory" was introduced in I4.0, in which computers and automation work together in a completely new manner (Benitez et al., 2020; Gupta & Basu, 2019). With the use of IoT, smart sensors, cloud computing, big data, and AI, it can learn and control the processes with minimum input from humans (Gupta & Basu, 2019). Delivering a more efficient and precise operations, reduced energy used, less raw material consumed as well as having a positive effect on the environmental impact (Gupta & Basu, 2019).

In I4.0, software does not simply become a bigger part of the value creation part in a product, but it targets at improving overall efficiency and quality of the whole value chain. As such, I4.0 covers more than just the "Smart Factory", including the communications among- and between machines, from machines to workers and between shopfloor and the back office. It reaches further than a single factory or company, involving all participants of the value chain, including the logistics (Schoning, 2018).

Matt et al. (2021) recalled that despite it being important on a firm-level perspective, I4.0 is a vast phenomenon that requires the participation of various actors, including firms, government, regulators, universities, and research centers (Benitez et al., 2020). With successful deployment, I4.0 based technology will be an essential part of the modern aluminum smelters and will be adopted by the existing plants in order to reach sustainability goals and remain competitive (Gupta & Basu, 2019). Ralph and Stockinger (2020) found that many producers do not fully capitalize on the potential of the fourth industrial revolution, the reason being a being low level of automation in their processes.

2.3 Technology and Humans

Companies are facing ever growing difficulties adapting digital transformation technology that is accepted and adopted by humans (Magistretti et al., 2021). The implementation of new technology and a not particularly tech-savvy users can cause resistance to change which slows the adaptation of a digital solution (Shirish & Batuekueno, 2021). Brunetti et al. (2020) showed that companies need to develop learning programs that allow individuals to upskill their technological competence. According to Belingheri and Neirotti (2019) the evolution of technological products require firms to initiate contact with other companies with different backgrounds than the focal firm, they further stated that firms often overlook the key benefits of new technology. Ralph and Stockinger (2020) acknowledge that a fear of job loss due to these disruptive technologies are contributing to the resistance to implementation, particularly in the metal industry. They are also concerned that interactions between humans and complex process optimization algorithms involve a particular challenge when implementing I4.0 solutions in the metal industry.

2.4 Innovation Ecosystem

A company's competitive advantage is dependent on its ability to create more value than their rivals, and greater value creation depends on the company´s ability to innovate successfully (Adner & Kapoor, 2010). Multiple empirical studies show the positive relationships between innovation and company performance. The studies underlined the usefulness of developing a corporate strategy and strategic management in the context of the company's internal capabilities, as well as the potential opportunities the external environment offer (Striteska & Prokop, 2020).

An innovation ecosystem is a way to create networks and focus on the cocreation of value (Benitez et al., 2020). A given innovation, often does not stand alone, instead, it relies on changes in the company's environment for it to be a success. Embedding the focal firm within an ecosystem of interdependent innovations (Adner & Kapoor, 2010). Benitez et al. (2020) proposed a framework in which an innovation ecosystem could consolidate and grow through different maturity stages, depending on a different setup of activities do achieve its purpose. Rong et al. (2015) stated that when the industry is very mature, the business ecosystem is quite closed, and control of the product or service should be in the hands of the focal firm, along with the product. Granstrand and Holgersson (2020) defined an innovation ecosystem as the following: **"*An innovation ecosystem is the evolving set of actors, activities, and artifacts, and the institutions and relations, including complementary and substitute relations, that are important for the innovative performance of an actor or a population of actors*".**

2.5 Digital Transformation in the Aluminum Industry

Dolgikh et al. (2020) stated in their article that the need for aluminum smelters to implement digital technology to reduce cost and increase quality was not an option but a necessity for Russian aluminum smelters to stay competitive. The increased market requirements for metal products quality and increased demand for highly processed aluminum products are one of the forces driving forward digital transformation in the aluminum industry (Dolgikh et al., 2020).

One of the challenges the metal production industry faces when it comes to digital transformation, is the high degree of heterogeneity in the industry (Ralph & Stockinger, 2020). Other challenges they mentioned are difficulties retrofitting existing equipment, human-machine interactions, high cost, and lack of standardization in Digital-Twin integration, organizations structure not equipped for vertical integration of the digital transformation, data security and ownership. The biggest challenge according to them was inadequate coordination with those responsible for production, and the internal IT department. We have evidence based on Sorger et al. (2021) research that Big Data is a core element of a value chain that is fully digitalized in the metal processing world. Digital transformation can aid manufacturers with decision-making along with process and operation optimization.

3 Methodology

This chapter discusses the methodological decisions made for this research, the research methods and techniques that contribute to solve the research problems. Describing a collection of methods adopted to accomplish the study's purpose. The research design, data collection method and data analysis method are discussed in this chapter.

3.1 Qualitative Research Design

This research adopted a qualitative research strategy intended to explore the aluminum industry with an innovation ecosystem perspective. The design of this research is done with the perspective of innovation ecosystem, adopting the language and vocabulary drawn from the concept. This research is not an analysis into a specific innovation ecosystem that exists in the aluminum industry. Although in the results and discussions chapters there are conclusions made where the aluminum industry is in general perceived as an innovation ecosystem.

The empirical problem of this research was initially discovered in discussions with employees at DTE, providing a brief description of the issues facing the company when innovating and implementing new technology. A case study can be used in many situations to contribute to our knowledge of an individual or group within a social system, such as organizations or industries. The case study allows researchers to retain a holistic and meaningful aspects of real-life events (Yin, 2003). A holistic single case study was an appropriate design as the study required inquiring rich and contextual data to explore digital transformation in the aluminum industry. This case study employees an explanatory approach.

3.2 Sample Criteria

The researcher reached out and conducted interviews with multiple individuals who work within, or in close relations in the aluminum industry in the Western world. The individuals background within the organization or firm had to be connected to research and development (R&D), digital transformation or automation in some sense. A adopted framework from the research of Matt et al. (2021) was used when compiling a list of individuals that needed to be interviewed for this research. These individuals included primary and secondary aluminum producers, suppliers of equipment and solutions, research facilities, aluminum clusters. A convenience sampling method was used to start the data gathering, interviewing individuals the researcher was familiar with in the aluminum industry. A network sampling method was then used to get referrals of individuals. The researcher conducted eight interviews in total, the interviews were conducted from September to October 2022. The list of interviewees and their roles within their organization can be found in table 1 below.

Table 1: List of interviews conducted

Role	Organization	Abbreviation	Duration
CEO	Aluminum Production Supplier A	APS-A	10 min
Executive Director	National Aluminum Cluster A	NAC-A	30 min
Executive Director	Research Facility A	RF-A	30 min
Head of Technology Development	Primary Aluminum Smelter A	PAS-A	40 min
Automation Program Manager	Primary Aluminum Smelter B	PAS-B	30 min
Senior Manager, R&D	Secondary Aluminum Producer A	SAP-A	50 min
Senior Research Scientist	Research Facility B	RF-B	30 min
CEO	Aluminum Production Supplier A	APS-A	25 min

3.3 Primary Data

The main source of data was a series of semi-structured interviews with members from the aluminum industry. These members were individuals working for aluminum smelters, a secondary aluminum producer, supplier of equipment, a national aluminum cluster and research centers. The interview guidelines can be found in appendix A. The purpose of the interviews was to collect information how digital transformation is affecting manufacturing processes in the aluminum industry. Another purpose is to capture information regarding the actors driving the changes in the industry. Qualitative data analysis software MAXQDA was used to assist with the process.

3.4 Secondary Data

In order to add on the amount of data the researcher had at his disposal, secondary data from aluminum producers was gathered. The author looked at lists from statistical database of Statista (Statista, 2021) and aluminum industry publication Light Metal Age (Pawlek, 2022). Then retrieved yearly reports, sustainability reports, environment, safety and governance reports or annual reports from the biggest aluminum producers worldwide. From both primary and secondary aluminum producers.

3.5 Data Analysis

This research used a thematic analysis (TA) as a qualitative analysis method. TA was used to identify, organize, and offer insight into patterns of meaning throughout a dataset. Two major reasons for the usage of TA in this research are its accessibility and flexibility. TA is flexible and allows the researcher to focus on analyzing meaning in the entire dataset or examine a single part of a phenomenon in depth (Braun & Clarke, 2012). In TA the coding is organic and open (Braun & Clarke, 2021). A top-down deductive approach to coding and analysis was chosen. A deductive approach in data coding and analysis in TA is a coding framework, where concepts, ideas and topics are brought on by the researcher to code and analyze the data. Meaning that what is mapped by the researcher during his analysis is not necessarily closely linked to the semantic data content (Braun & Clarke, 2012). Thematic framework analysis was used on the interview transcripts to identify, describe, and interpret key patterns within the qualitative data. The framework analysis was done in six stages. An adaptation of the six-phase approach to TA from Braun and Clarke (2006) was used.

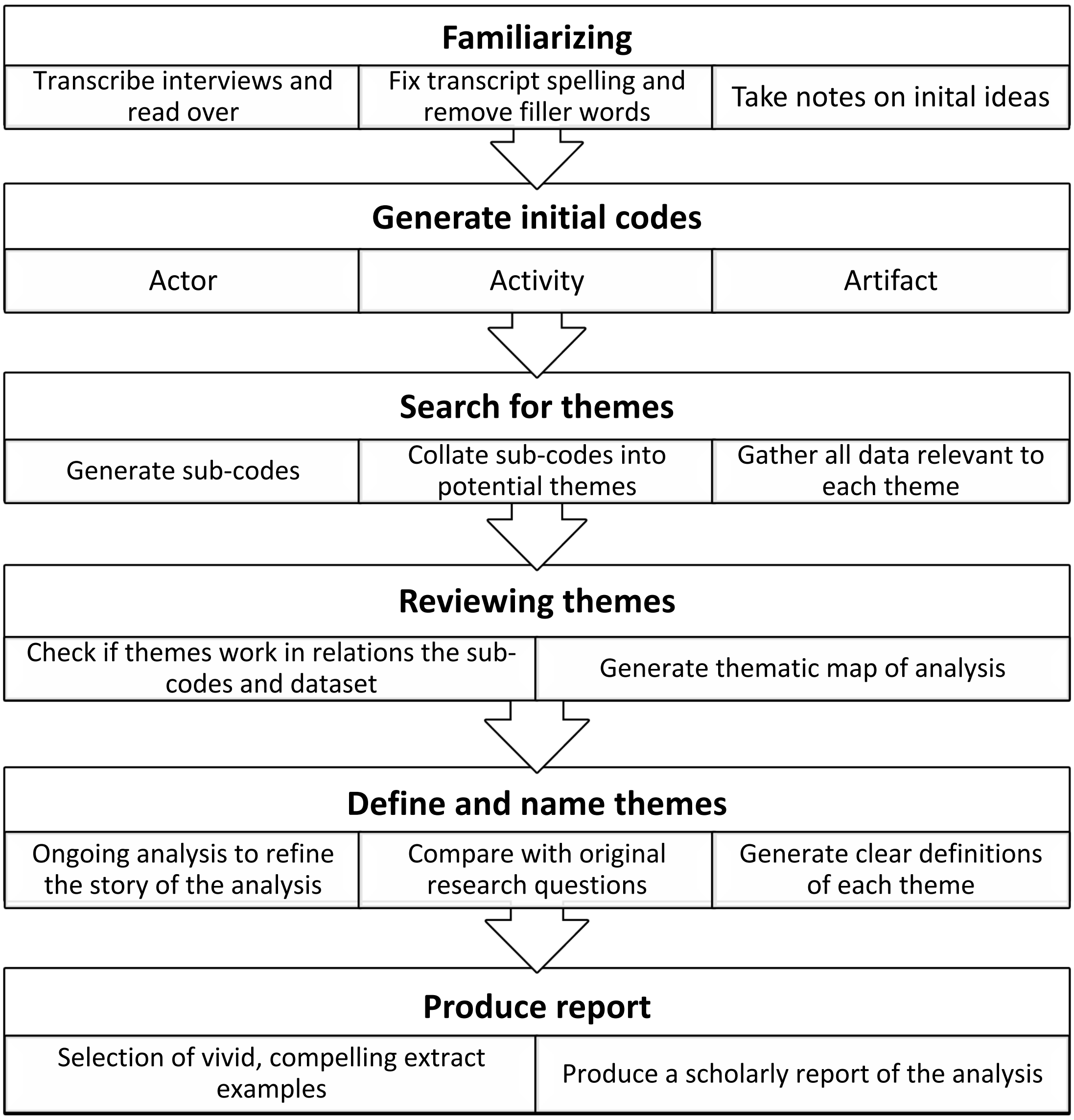

Figure 3: Six-phase approach to thematic analysis (Adopted from Braun & Clarke, 2006)

3.5.1 Familiarizing

First, all the interviews were transcribed into text documents. A transcription software named Descript was used to assist with the process. Unfortunately, the software could only be utilized on interviews conducted in English. Two of the interviews were in Icelandic, the transcripts of those interviews were manually transcribed into text documents. Then spelling mistakes and filler words were removed from the transcript. The transcripts were read over and simultaneously notes on initial ideas regarding the data and the research were taken.

3.5.2 Generate Initial Codes

Next, initial codes for the analysis were generated. Three codes adopted from research done by Granstrand and Holgersson (2020). The codes were actor, activity, and artifact. Paragraphs of the transcripts were labeled with appropriate codes.

3.5.3 Search for Themes

Phase three started with the creation of sub-codes. The sub-codes were connected to the codes initially generated, and the sub-codes applied to the paragraphs. Then the paragraphs were divided into smaller sections of text with appropriate sub-codes. The sub-codes were then collated into potential themes and the data surrounding each theme was then gathered together.

3.5.4 Reviewing Themes

At this point, revisions into the themes and sub-codes were conducted. New sub-codes were created, old sub-codes were deleted or merged, and all transcripts needed to be revisited and re-coded with the final version of sub-codes. After which a thematic-map or a narrative of the data could be outlined.

Table 2: Transcript codes and sub-codes

Actor	Aluminum Cluster	**Activity**	Funding	**Artifact**	Bottleneck
	Aluminum producer & Operators		Innovation		Data
	Research Center & University		Networking		Value Adding
	Supplier		Orchestration		
	Unions				

3.5.5 Define and Name Themes

In phase five, there was an ongoing analysis into themes, sub-themes, and narratives. Themes were compared with original research questions and theoretical review. Refining the specifics and the story of the analysis, then creating clear definitions and names of each theme.

3.5.6 Produce Report

During the sixth and last phase, a selection of compelling extracts from the data were selected, edited, and then implemented in the report. The data was interpreted into an analysis of the themes and sub-themes to communicate the narrative. As some of the interviews were not conducted in English, the extract examples from those interviews needed to be translated before being included in the report.

4 Results

In this chapter, analysis of the interviews conducted with players in the aluminum production industry is presented. A number of themes were discovered when looking at the data with the mindset of innovation ecosystem. First, six different actors are identified within digital transformation in the aluminum industry. Then networks surrounding innovation in the aluminum industry are explored. Lastly, changes in aluminum manufacturing are examined.

4.1 Digital Transformation Actors

There is a number of actors that operate within the aluminum production industry that affect its digital transformation process. Aluminum producers and operators, suppliers, research centers and universities, aluminum clusters and unions all have their roles and influence the transformation.

4.1.1 Aluminum Producers

My research shows that aluminum producers are focal actors in the digital transformation that is happening in the industry. They already have the infrastructure needed, sizable R&D departments and resources earmarked digital transformation or product development. They are however limited in that sense that they do not necessarily have all the capabilities to push projects forward on their own. The problems might be internal conflicts between different silos in the company, or it might be a lack of certain competence or knowledge they need to bring into the equation from an outside source. All but one of the interviewees mentioned this, the only exception being Research Facility B (RF-B). As Aluminum Production Supplier A (APS-A) said: ***"Companies alone and users alone cannot do it themselves, they need to partner with suppliers, research organizations, and the government."***

Operators of equipment and machines within an aluminum producer can be recognized as an actor as well. Operators can have tremendous influence over the decisions that aluminum producers take relating to digital transformation in their production processes. Operators are further examined next, the affect they have on the development of digital transformation projects in the aluminum industry.

4.1.2 Operators

With more data you can take faster and better-informed decisions, but a multitude of decisions taken is in the hands of the operators of machines or equipment. As people in general can be reluctant to embrace the technological shift that accompanies the digital transformation and I4.0 implementation. If you do not include the operators when it comes to product development, the project will face pushback and the implementation will often fail. Primary Aluminum Smelter A (PAS-A) said in the interview: ***"Often a good technical solution isn't practical enough or intuitive enough. People think it's too complex to operate, then it's put aside, so they use the old system instead."*** Digital transformation projects can highlight the technological incompetence of operators, education on digital technologies are required to fill that gap for useful applications of the technology (Brunetti et al., 2020).

People or operators are a major actor in the digital transformation scene. They have both the power to hinder product development or implementation, as well as they can assist and speed up the development. Their knowledge on the current equipment and processes makes them vital to any digital transformation in the aluminum industry. All aluminum producers pointed this out, as Primary Aluminum Smelter B (PAS-B) said in the interview: ***"I find [Nationality] especially receptive to new features and solutions. Especially if everyone is included from the start. That is key, include everyone, people on floor as well."***

Digital transformation is changing the ways people operate in the production process. Instead of relying on experience and insight when taking a decision, operators' jobs are becoming more of a caretaker of the equipment. The technology takes the decision or. at least advice the operator on what should be done. The critical decision making is assisted by technology, catering to more unified decisions, as mentioned by PAS-B: ***"Often today we have employees on shifts, and it is a different individual on each shift taking critical decisions on what is produced."***

4.1.3 Suppliers

Suppliers of equipment and solutions play an important role in the digital transformation of the aluminum industry. Aluminum producers are regularly approached by different suppliers and offered a solution. Aluminum production is a complex process and there is seldom an off the shelf product that solves the problem. Value propositions are usually customized for each customer in order to fit their specific needs. But many of the products that are developed in collaboration between aluminum producers and suppliers can be deployed in other industries as well. This makes the equipment or solution more scalable and more economically viable, but there are always issues between actors regarding intellectual property that need to be resolved. There is a consensus among some of the major players in primary aluminum production that their suppliers need help in developing their products. This benefits not only both actors but the whole value chain. PAS-B mentioned that: ***"We talked to [Aluminum smelter X] and we talked to [Aluminum Smelter Y], to agree with them, that we need to develop the suppliers for our industry. Because they are the key people who know their equipment much better than we do."***

If the proposed solution of the supplier does not help the aluminum producer from an industrial standpoint or does not fit properly in the vision of the company, there will always be difficulties. However, if the solution or device the supplier proposes does align with the aluminum producer, the supplier will hit the ground running in a sense. Secondary Aluminum Producer A (SAP-A) said that: ***"If the problem is, we need to be carbon neutral by 2050, and you come up with an idea that gets you to do that. That idea is going to get the innovation moving. That idea to impact is going to get a lot of focus and the red tape just disappears."***

4.1.4 Research Centers & Universities

Research centers and universities effect on innovation and product or equipment development in the aluminum industry is apparent in a supportive role. The aluminum industry or its supplier frequently reach out to research centers or universities to assist them, providing the required knowledge or expertise they lack. On the other hand, research facilities and universities often require support or the infrastructure of the aluminum industry when conducting research or developing a product. The aluminum industry can provide an environment for real-world testing on the subject.

The academic community and research facilities are usually not interested in lingering around a product or innovation once it goes into production or is implemented, they are more interested in finding something new to turn their attention to, as stated by Research Facility A (RF-A), for example: ***“I have colleagues that don't care because they just want to invent it, and then they are finish with it.“*** Another risk is that a singular professor that has a background or passion in a particular field can move positions or leave the university and with that, the knowledge and support in their field disappears from the industry.

4.1.5 Aluminum Clusters

A multitude of aluminum clusters have been born around different areas of aluminum production. You can find aluminum clusters that are centered around a geographical location as well as different industrial usage of aluminum. For example, centered around the increased usage of aluminum instead of steel in automobiles. When developing these clusters, aluminum producers need to look at other members as not competitors but collaborators. Members must strive to build up trust between members, this stimulates innovation in the cluster and new business opportunities open up.

> ***I recently read an article that we're going to partner with some of our other competitors. To make the aluminum can, mono alloy, because the aluminum can is two alloys actually. Which I thought was crazy, because we have spent so much time of our own and research money. But now I've heard that we're going to do that, because it is such a big topic, especially around the recycling industry. That we are now going to partner with our competitors and try to come up with a solution. (SAP-A)***

4.1.6 Public Bodies

Multiple governments give substantial fundings or grants to projects that support or is in line with sustainability or workforce environment objects of the government for example. This can sometimes be crucial when decisions regarding whether to go forward with a project are made. There is however some governance that comes with it. Companies that receive these fundings or grants need to follow certain rules and requirements regarding how money is spent and tracked. Both primary and secondary aluminum producers mentioned this when our discussions pivoted towards government grants. As described in the interview with PAS-A: “***We often look for how you can get support from this governmental grant. This is in financial terms called de-risking the project, and sometimes feels that this project will not start without this kind of grant.“*** This point came up in discussions between me and RF-A and, APS-A as well.

4.1.7 Unions

Not all changes that come with digital transformation of the aluminum industry are met with enthusiasm of all parties. Unions for example, can be negative toward digital transformations that for them carry the risk of reducing the number of jobs at an aluminum production site. Unions pose a great deterrent in these matters, employees or operators can have the same effect as they sometimes believe that an equipment or technology will replace their jobs. Two of the interviews I conducted mentioned this fact, PAS-A mentioned as well that if projects are presented in the correct manner to unions and employees, the initial hindrance can be removed, and the project goes forward:

> ***Then there was a discussion with the unions because the unions are a little bit afraid that we take away their workplaces. We discussed it with the unions, and then together we figured it out. Let's start on the project, which has an environmental impact, and this is dirty work for people, in which people can get hurt or exposed to emissions, which are not good for their health. So, for this kind of work, the unions didn't defend either, they agreed that these areas should be removed or automated. (PAS-A)***

4.2 Digital Transformation Activities

My research classifies activities between the actors in the aluminum industry into three groups, networking, funding, and orchestration. Networking and building relationships are important in product development and innovation in the aluminum industry. Funding is necessary for innovation projects and is often provided by government grants at the beginning stages of product development. The orchestration of these projects varies, with some organizations preferring to lead and others preferring a more collaborative approach.

4.2.1 Networking

All of the interviewees mentioned the importance of networking and the effect that can be made to product development and innovation through it. It can be as simple as attending a conference or seminar and meeting another individual and an idea is born through that discussion. These individuals often have a vast knowledge into a certain subject and are connected to a major network in that field. Clusters of knowledge then start to form around an idea, product development or a certain innovation.

> ***In fact, there was a conference, [...] where we had several representatives and the professors that were presenting their papers would then come to [Secondary Aluminum Producer A] representatives during that conference and say, I'm really looking for an industrial partner that wants to work with me on this work. That's how they seem to get in touch with us. (SAP-A)***

RF-B noted that the most important part of a good network are friends, where a phone could be picked up and open trusted discussions regarding an idea made with ease. Aluminum clusters are an important aspect of this network. Individuals meet, often face-to-face and this helps in developing relationships and building trust. This fact was noted by both PAS-A and SAP-A.

> ***We try to make a cluster of this competence centered so we could meet together. [...] Then we connected the university in [Country A], in [Country B], in [Country C] and, in [Country D], which have very clever research groups. So, we tried to put up some programs together where we could exchange information, have programs together, and also develop people who could be interested in understanding this business better. (PAS-A)***

4.2.2 Funding

Many innovation companies and projects in the aluminum industry are funded by government funds at the beginning. The research and development phase can be quite long, and expensive, small companies do not have the necessary financial resources. Bigger corporations do however have the financial muscles required for these projects. These corporations are however not shy of utilizing these funds when they are available to them. SAP-A said that they are prone to seek government funds in Europe or Canada than the US. Not due to stricter requirements but because the governance needs of the funds tend to be trickier and harder to manage. SAP-A mentioned this regarding funding: ***"It takes almost a whole team of people within your company to make sure that all the governances are put in place correctly.***

Funding a project in a major corporation can be tricky. The projects sometimes require both capital expenditure (CapEx) and OpEx from different silos of the company. APS-A pointed this out: ***"Digitization brings efficiency and sustainability, and who pays for this? If it's the process efficiency, the guys from efficiency, if it's digital transformation, if it's the environmental person. You can impact different things and it's always the question, who pays?"*** When pursuing digital transformation projects there is usually never a clear timeline or funding, due to how unclear the R&D phase often is. PAS-B commented this when our discussions revolved around funding: ***"There needs to be understanding present that when you are initiating digital transformation projects there are phases that are pure R&D. Then you do not know precisely the timeline or funding required for the project."***

The funding of these projects is usually in the hands of the corporation or individuals that are driving the R&D phase forward. Due to the growing interest in I4.0 within governments, there is increased funding available to projects that fit a certain criterion. These criteria commonly revolve around The United Nations Sustainability Goals.

4.2.3 Orchestration

There was not a clear consensus between interviewees how orchestration of these digitalization projects was managed. RF-B said that they prefer being in the lead of the projects they are involved in, due to their foremost position on scientific or technological side: ***"I like to be the lead, not the administrative lead. […] I like to make it happen."*** RF-B recognized that is not always the case and can be dependent on the nature of the project. RF-B acknowledged cases where they are not in the leading position scientifically and need to deliver leadership to another individual. SAP-A mentioned as well that the orchestration of the project varies.

Often suppliers will contact the aluminum producer and pitch them an idea. In the development of that idea, then usually it is the supplier the one orchestrating and pushing the wagon forward. APS-A agreed, that for their projects, they are the movers and shakers. Their projects success is depended on many factors, one of them being that they need to be resilient in driving the effort forward, stating this: ***"We are driving digital transformation, so we are bringing this digitization to [Product Solution]. We are part of the transformation projects inside the customers. We are the ones driving the digital transformation."*** My research shows that the orchestration of digitalization projects in the aluminum industry usually is the responsibility of the individual or organization that possesses the greatest knowledge on the technology or science used for the digitalization.

4.3 Digital Transformation Artifacts

There were three artifacts discovered in my research of digital transformation in the aluminum industry, data, bottlenecks, and value adding. My research showed that data collection and analysis is important in implementing Industry 4.0 solutions in the aluminum industry. However, data quality and sensor performance can be issues, as well as a lack of standardization in data collection. The industry has traditionally focused on reporting rather than predictive analytics, and there are various bottlenecks that can hinder digital transformation projects, including difficulties in decision-making and trust-building between customers and suppliers, as well as a lack of clear value proposition for the customer.

4.3.1 Data and Digital Transformation

The foundation of implementing I4.0 solutions is a proper data collection pool, which you apply the appropriate techniques or solutions to solve your problem. The aluminum industry has put effort into implementing various sensors and collecting datapoints for decades. SAP-A had this to say when the subject of data arose: ***"I would say data is the biggest contribution on digital 4.0, mostly because you cannot tackle a problem unless you are able to collect enough data to be able to understand the problem."***

On the other hand, the data collected is not always of the proper quality. Meaning that the data collected could be from measurements not accurate enough to apply machine learning for example. Also, the industrial setting in aluminum production can be troublesome for sensors, due to heat, dust, and magnetic fields for example. The data points collected do not follow a standardization in which you can then apply different algorithms on it in order to make a decision, solve a problem you have, or achieve the desired outcome. PAS-A stated in the interview: ***"So if you hire an, what you call an analytical person to do this with a computer science background, he needs to spend 80% of his time just to see to that the data can be used."***

The aluminum industry has been focused on the reporting side of data. Notifying them what has happened, they need to shift that focus towards predictive analytics to advise them on a decision or take it automatically. Removing or minimizing risks that arise from having different operators taking decisions that are crucial to the production process, resulting in a more uniform production process. All aluminum producers recognized data as one of the most important aspects of digital transformation projects.

> ***If you have more info, you take better decisions, faster decisions. and safer decisions, and there is one more, unified decisions. Now what means better decision when you have more data? You take more informed decision, and faster, because today the information comes after whatever. So safer decisions because you have more data, therefore you're going to make less mistake and unified decisions. (APS-A)***

4.3.2 Project Bottlenecks

The respondents had different opinions on what the bottlenecks of the digital transformation projects were. First two similarities were the people in plants or operators of equipment, mentioned by both APS-A and PAS-B. This point has been discussed before in chapter 4.1.2 Operators. APS-A mentioned the difficulties as well that arise with the customer and supplier not establishing a clear enough communication from the beginning. Resulting in the provided product or service not being what the customer had in mind. This also means that decision making and conveying those decisions is not efficient enough, slowing the product development process. APS-A said when discussing bottlenecks in projects that require a customer's input or decision: "***The bottleneck is to take a decision. Once they take the decisions, the project moves, it moves slowly, but it moves.***"

Similarities NAC-A and RF-B talked about, was the difficulties with starting these digital transformation projects with regards to trust. The processes in place are highly optimized and the threshold for individuals to bring about changes to them is quite high. It requires trust from both parties to try to solve a problem or bring forwards new ideas and implement them. Earning that trust to set your foot in the door to start testing can take time.

> ***You are an entrepreneur, and you are faced with this big industry with all its processes tremendously optimized. There is much at stake for everything to work as planned. This industry is built on a technology that first came forward a 100 years ago. Then there is of course a threshold, and a lot of trust is needed to come in to test these new ideas. (NAC-A)***

Another threshold that is evident with starting these digital transformation projects is insufficient or unclear value for the customer with adapting these solutions. The customer is hesitant to put too much effort in the transformation process and scared of the results it brings. It can lead to insufficient funds being directed to the project, this point was made above in chapter 4.1.3 Suppliers by SAP-A.

PAS-A remarked that the complexity of these digital transformation projects is a bottleneck. Every low hanging fruit is already picked and harvested, the remaining issues are very complex and any solution to the problems is not so easily integrated. Another issue on the complexities of these projects is that often the available technology is not available yet. Best described by PAS-B when discussing a major I4.0 implementation project: ***"I know I cannot***

go all the way yet. The program will take 10 years, so why not start at this point and expect that the technology will be ready when we need it."

A similar view appeared in my talk with RF-B, the real bottleneck is keeping up the commitment of individuals working in the project. As projects move along, there can be some hindrances that seem impossible to overcome and can cause disinterest in the project. Finances of the project drying up can also cause a disturbance, as noted by RF-B: ***"I think it is to keep on the enthusiasm. If the money disappears, many people cannot work on it. That kills enthusiasm or engagement or whatever word you want to use."***

4.3.3 Value adding

The digital transformation of the aluminum industry has multiple value adding results. That can be raw material optimization, energy usage reduction, increased production or better process control, along with increased equipment life (Dolgikh et al., 2020; Gupta & Basu, 2019; Kvande & Drabløs, 2014). SAP-A and PAS-A were in an agreement that value needs to be shared between the aluminum producers and their suppliers. Best described by SAP-A: ***"We want our suppliers to succeed as much as possibe. Even though we do need a certain price or output, we're here to make our suppliers stronger."***

4.4 Changes to Aluminum Manufacturing

The aluminum industry has a broad spectrum of projects aiming for increased efficiency, innovation, and digital transformation ongoing. Three interviewees mentioned that their plant or location has a different roadmap or emphasis on types of projects to other locations in their organization. Both primary and secondary aluminum producers said that there is a certain emphasis on projects from the administration, but in general, each location is an independent unit and operates as such. Information regarding those projects was retrieved from both the interviews conducted as well as found in reports from actors in the aluminum industry.

4.4.1 Different Projects

Although only three individuals that worked directly in aluminum production were interviewed, all interviewees gave insight into what kind of digital transformation projects the industry is currently operating. With industrial automation being one of those projects, where more than one factory is connected in order to automate production of customized products for the customer. The product will be tailor made, mass-customizing replacing mass-production. Digitalized and flexible plants are operated through automation of processes. National Aluminum Cluster A (NAC-A) discussed this: ***"We were looking to the future for opportunities. […] There we discussed for example the importance of on-demand development. Where smaller and more specialized implementation of products and how does the aluminum industry fit into that."***

Digital Transformation in the aluminum industry can change the way production processes adapt to faulty equipment that cause interruptions to the production processes. PAS-B remarked during the interview that the system controlling the production process can automatically take into consideration the effect a broken equipment has on the processes and make appropriate alterations.

> ***Of course, you have a plan and it based on a perfect world. Then you have equipment that breaks down and the plan changes. What we are missing and are hopefully starting to develop is a system that takes a snapshot of the current status, this is what we should be producing. Then a overhead crane breaks down and new production plan is developed and distributed to the whole chain of processes. (PAS-B)***

Transportation of recourses and operations of equipment is progressively becoming automatic, without the input of the human hand. In order to optimize those automated factories and systems, a simulation of the processes needs to be in place. Primary and secondary production is a complex process. A single simulation is not able to properly represent the processes. A DT is a concept that could aid in simulating such a long value chain (Gupta & Basu, 2019).

Automatic industrial imaging analysis is being implemented in aluminum production. This imaging allows for automatic process changes in various scenarios. Imaging can be used for preventive maintenance as well as quality assurance of the product produced. Neural networks and deep learning can be used for imaging to see abnormalities in end products for example. PAS-B mentioned this: ***"We are for example running two projects that use neural networks and deep learning for imaging."***

LP-LIBS applications in real-world situations has recently been demonstrated after earliest reports of LIBS on molten steel samples going back half a century (Gudmundsson et al., 2019) and on molten aluminum at least 25 years (Gudmundsson et al., 2020). The technology eliminates time consuming, error prone, and dangerous sampling processes that are used today in aluminum production. DTE's IREAS online data gathering and prediction system aids with process control in the aluminum production industry. Such as pot-tapping schedule and pot maintenance and quality control in the potroom of primary aluminum smelters (Areces, 2021a). The IREAS system can integrate with I4.0 solutions in both primary and secondary aluminum producers with aluminum composition information being converted to actions in real time through the whole process chain (Areces, 2021b).

4.4.2 Projects Origin

The major aluminum producers, both primary and secondary mentioned that they have in place roadmaps for digital transformation within their production. These roadmaps were the product of major workshops performed by the producers. The workshops included employees on all levels of the organization, from operators of equipment to administrative staff.

> ***What we started with first was that we interviewed a lot of the plant people. Where they thought there could be potentials and got together with the team from [university group]. We facilitated all these interviews to help the plant to identify areas. So, we made a list of maybe 500 projects with improvements possibilities. (PAS-A)***

Aside from being potential bottlenecks in the product or solution implementation, operators are often the ones with the best understanding of the environment and have a great insight into how the problem can be formulated. With that information, operators often come up with suggestions or proposals of product development that is closely linked with their day-to-day operations. PAS-B and SAP-A both had remarks on this issue.

> ***It was a project on simulation and optimization on the aluminum production. It was an employee that performed it, he basically showed what could be archived by performing a basic simulation of the flow. We then use all the work he performed in a bigger project. It's a huge transnational project involving three smelters. (PAS-B)***

My research shows that many major aluminum producers, both primary and secondary use an employee suggestion program to encourage employees to initiate potential changes to current production processes. Those suggestion programs originate from the continuous improvement and innovative culture of the aluminum producers, encouraging and rewarding innovative thinking at all levels of the production. Empowering employees to bring forward their ideas for incremental and large-scale improvements (AG, 2021; Befesa, 2021; EGA, 2020; Hydro, 2008; Limited, 2021; Rusal, 2021).

Suppliers and entrepreneurs also have the capabilities to drive forward a digital transformation project. Many projects originate in the head of entrepreneurs, they then develop the product or solution. Often the entrepreneurs are well connected within the aluminum industry, this fact aids them in obtaining the assistance they might need from the aluminum industry. Both APS-A and NAC-A both pointed this out in our discussions.

> ***If we take a look at our projects within [NAC-A], how they have originated. We can take two examples, one where two specialists from the aluminum industry have the industry knowledge, are well connected, and develop a product. [...] Another example is of an individual that brings a project from another country. The individual has already been driving the project forward in [Country], brings a certain competence and specific equipment with him. Then needs professional assistance and cooperation regarding funding. This is where [RF-A] comes into the picture as a powerful partner. (RF-A)***

5 Discussion

This research project was carried out with the aim to explore the digital transformation that are taking place in the aluminum industry and explore the effect they have with the perspective of an innovation ecosystem. Find and examine the different actors that reside in the field of aluminum production, discover their relationships in product innovation or development. To assist DTE in their participation in the digital transformation of the aluminum industry, this research project seeks to answer the following research questions: ***How are actors of the aluminum industry driving the digital transformation in the industry, and how is digital transformation affecting manufacturing processes in the aluminum industry?***

The key findings are summarized and interpreted in this chapter. The different actors and their roles, the changes in aluminum industry that come with digital transformations along with the limitations of this research and recommendations for future research related to this field. A number of key themes were identified, including the actors involved in the industry's digital transformation, the networks surrounding innovation, and the changes taking place in aluminum manufacturing.

5.1 Actors Driving Digital Transformation

I found a number of actors who were operating within the digital transformation of the aluminum industry. The most obvious ones being aluminum producers, as the focal firm of innovations in the digital transformation of the industry. Aluminum producers surround themselves with complimentary actors that play a unique role in driving innovation in the industry. Granstrand and Holgersson (2020) recognized the importance of actors, institutions, and the relations between them. These actors include suppliers, research centers, universities, aluminum clusters and public bodies. Results show that aluminum producers have the infrastructure, R&D departments, and recourses to drive forward the product development in digital transformation of the industry. Furthermore, I also found that they may not have all the necessary capabilities to advance projects on their own, and rely on other actors such as suppliers, research organizations and universities to bring the necessary knowledge or expertise that Matt et al. (2021) found necessary for I4.0 adaptation. This contradicts the findings of Striteska and Prokop (2020) which stated that in-house R&D is the most positively significant innovation activity.

Aluminum production suppliers are important actors in the digital transformation of the aluminum industry. Suppliers have the capabilities that aluminum producers do not have that are necessary to develop these complicated solutions. My results show that working in collaboration with both the aluminum producers, and other actors, they can provide their customers with complex systems that benefit all actors. I4.0 solutions are a complex system of interconnected information and process technologies, demanding a high interdependency of competent actors (Benitez et al., 2020). The solutions are often customized to fit the specific needs of individual aluminum producer (Matt et al., 2021). Suppliers need to be wary of the value proposition they present to aluminum producers, according to Adner and Kapoor (2010) the focal firm faces two uncertainties from their suppliers. One being the technological uncertainty whether and when supplier delivers on their own development challenges, which this study confirms. Aligning the proposed solution with the customers vision or goals is crucial for the success of the project. My results agree with Adner and Kapoor (2010) that firms face considerable challenges surrounding development and production of an innovation.

The academic community and research facilities provide institutional coordination for digital transformation projects that is fundamental to the development of digital transformation technology. I found that the aluminum industry approaches research center and universities to fill the knowledge gap that exists in the development of digital transformation technology. This supportive role is dyadic in a sense that aluminum producers are often the ones supporting universities and research facilities by providing, the necessary infrastructure or artifacts required for purposes that benefit the aluminum producers.

Other actors are aluminum clusters and government bodies. Regional aluminum clusters facilitate network systems and create platforms for collaboration between different actors working in the aluminum industry. Enabling actors to share ideas, expertise and collaborate on complicated issues facing the industry. This allows them to combine complex value propositions for their customer, the research of Matt et al. (2021) confirms my thesis by showing the importance of such clusters for development and adaptation of I4.0 solutions.

Public bodies such as government agencies and funding organizations, provide financial support for digital transformation projects in the aluminum industry. Results shows that due to the environmental impact the metal industry carries, there are government grants easily available to actors in the aluminum industry, Matt et al. (2021) showed the importance that financial resources implementation of new technology. I found that government act as a major external supporter, suggesting that any aluminum industries innovation ecosystem is quite immature, Benitez et al. (2020) study found that government presence becomes progressively weaker as the ecosystem matures.

Finally, operators of machinery and equipment of the aluminum producers can also be viewed as actors. They are highly influential in the design process and the implementation of the digital transformation in the aluminum industry. Results show that operators need to be adhered to the design of the digital transformation solution from the start, the research of Magistretti et al. (2021) confirm this. However, Belingheri and Neirotti (2019) discussed that users tend to be too incremental and focused on existing products, limiting the effect the product development has. Brunetti et al. (2020) found that tenured employees of organizations need to attend more training courses on technology than the younger generation. By providing insight into the challenges and opportunities facing the industry, operators help shape the direction of digital transformation projects and ensure that they are aligned with the needs of the industry.

In addition to examining the different actors in the digital transformation of the aluminum industry, this thesis explored the networks surrounding innovation in the industry. These networks are complex and dynamic, with a wide range of connections and relationships between different actors. These networks can facilitate collaboration and the sharing of knowledge and recourses, but can also create tensions, such as disputes over intellectual property, and competition for funding and performance. The research of Benitez et al. (2020) on I4.0 innovation ecosystems showed that a neutral orchestration between the companies and universities meant that the innovation ecosystem was fairly mature, my results show that aluminum producers and suppliers do not practice this neutral orchestration.

5.2 Changes To Aluminum Manufacturing Processes with Digital Transformation

Dolgikh et al. (2020) research results showed that one of the key changes taking place in non-ferrous smelters is the increased focus on sustainability and reduction of carbon emissions. This fact is driving the adaptation of new technologies and processes that are more energy efficient and have a lower environmental impact. This includes the use of sensors and data analytics, which agrees with my research on aluminum production. In addition to the adaptation of new technologies there is a growing trend towards digitalization and automation in the aluminum industry.

I found that increased adaptation of I4.0 solutions and use of sensors to measure the performance of equipment, machines and operators, data analytics and artificial intelligence can then be used to assist with decision making, identify opportunities for optimization and improvements agreeing with Dolgikh et al. (2020). Ralph and Stockinger (2020) work on digitalization in the metal industry stated the difficulties with amount of data and its variety, those issues addressed echo with my findings. I do not agree with Ralph and Stockinger (2020) that heavy industries biggest issue with big data is it not being entered into the database.

Gupta and Basu (2019) research into the future of technology of aluminum production examined the use of inert anodes, DT and the importance of modeling when making incremental changes to equipment and procedures. My findings support Gupta and Basu (2019) statement about modeling and DT but no mentions of inert anodes were made in my interviews.

Another key change that is taking place in the aluminum industry is the growing importance of collaboration and networking. I agree with Adner and Kapoor (2010) who stated that innovation challenges are often situated outside the focal firm, within other actors in the firm's ecosystem. The results suggest that aluminum producers are not fully realizing the importance of actors collaborating, sharing knowledge and recourses in order to drive innovation and stay ahead of the curve in the aluminum industry, as it becomes increasingly competitive and complex. Benitez et al. (2020) stated the importance of trust to foster commitment and reciprocity between different actors in I4.0 projects, which I found lacking in the industry. They stated as well that companies are not willing to start a cooperation with other actors unless the benefit was clear to them, usually in the form of reduced cost, I find that the aluminum industry has this individualistic view described by Benitez et al. (2020).

By using innovation ecosystem perspective, the results show me that there are incentives and funding is available to aluminum producers, suppliers, and research centers for I4.0 solutions development. Results also show that training and the education of employees in adopting digital transformation technologies is lacking in the industry. I found as well that aluminum producers are dependent on other actors for many innovative projects that the digital transformation of the industry relies on. In turn, suppliers, research centers, and universities are reliant on aluminum producers to provide them with the necessary infrastructure for R&D of those solutions. The study of Benitez et al. (2020) noted the importance of innovation, resource and knowledge sharing that is needed for the development of complimentary products, my results show that the aluminum industry is lacking the trust needed for the development of these complex solutions required for the implementation of I4.0.

Overall, the changes taking place in aluminum manufacturing are driven by a variety of factors, including environmental issues, operator safety, enhanced process efficiency, adaptation of new technologies and the growing importance of collaboration. These changes are shaping the direction of the industry and will continue to have a significant impact on its future development.

5.3 Limitations & Future Research

The use of thematic analysis was appropriate to fulfill this study's aim and answering the research questions. However due to the competitive nature of the aluminum industry the number of interviews conducted, and the data extracted from them was limited. Some of the interviewees were skeptical of being interviewed, in fear of exposing trade secrets and corporate espionage. This fact impacts the scope of the research and its true value. All the actors interviewed are located in the western world, limiting the scope and application of this research. The limited number of interviews conducted in this study also narrows the scope of the data collected and affect the validity of the findings. The fact that no interviews were conducted with educational institutions hinder the collection of data regarding the educational aspect of innovation ecosystems.

Future research into digital transformation in the aluminum industry should include the educational aspect and the effect it has on digital transformation in the industry. Despite being an important actor in digital transformation, no interviews were conducted with operators of machinery and equipment. A study on the challenges the industry faces when developing and adopting digital transformation solutions must include the perspective of the operators.

This research provides a snapshot of the digital transformation in the aluminum industry with the perspective of an innovation ecosystem. This approach can be deployed to do a comprehensive analysis of an aluminum innovation ecosystem, measuring its innovative performance. Future research should focus on understanding the specific challenges and opportunities faced by these actors in the aluminum industry and how they can work together to drive innovation and sustainability in the industry.

5.4 Implications

This study extended the understanding of the digital transformation in the aluminum industry and the challenges the industry faces when implementing I4.0 solutions. It contributes to digital transformation literature by identifying and mapping actors, activities, and artifacts in digital transformation of the aluminum industry from an innovation ecosystem perspective.

The study provides managers of DTE with a collection of problems and hurdles present when implementing their technology in collaboration with their customers. One identified framework that might be necessary for the managers of DTE when it comes to setting the strategy of innovation for the company is based on the work of Benitez et al. (2020). DTE's innovation ecosystem is in the birth life cycle stage and if they wish for their ecosystem to reach expansion stage, they need to adopt cooperation strategies and use an open innovation approach. DTE's desire to be a leading supplier of their solutions technology in the industry means that they need to shift from only collaborating with aluminum producers to committing in a strategic alliance with suppliers of equipment's for complex project value propositions. DTE's desire to be a leading supplier of their solutions technology in the aluminum industry means that they should position themselves as a focal company in the development of these complementary solutions. Benitez et al. (2020) study observed the importance for small and medium enterprises industry 4.0 ecosystems need to include integrators and add-on technologies the customer might need.

6 Conclusion

In conclusion, the aluminum production industry is undergoing a process of digital transformation that involves a range of actors that have a say in and influence on the transformation process. These actors include aluminum producers, suppliers, research centers and universities, aluminum clusters, and public bodies.

Each of these actors play a unique role in the innovation and development process within the aluminum industry. Aluminum producers have the infrastructure and resources to drive digital transformation forward but may need to partner with other organizations to bring in specific expertise. Suppliers offer customized solutions to fit the specific needs of aluminum producers, but there may be issues surrounding the adaptation and implementation of the solution. Research centers and universities contribute to the innovation process through research and collaboration with industry partners. Aluminum clusters facilitate a network of actors that come together to innovation within the industry. Public bodies, support and promote innovation through funding and other resources. Overall, the digital transformation of the aluminum industry is a complex process that involves the collaboration and cooperation of many different actors.

Digital transformation in the aluminum production industry is leading to a number of changes in manufacturing processes. One major change is the increased use of automation and data analytics to improve efficiency and productivity. With the help of sensors and other technologies, manufacturers are able to collect real-time data on their operations, allowing them to make more informed decisions about how to optimize their processes. This can include identifying bottlenecks, optimizing equipment utilization, and predicting maintenance needs.

Another change brought about by digital transformation is the increased use of advanced manufacturing technologies. These technologies can enable manufacturers to create customized products more quickly and efficiently and can also allow for more flexible and agile production processes. Digital transformation is also leading to an increased focus on sustainability in aluminum manufacturing. With the help of data analytics and other technologies, manufacturers are able to better understand and track their environmental impact and identify opportunities to reduce their carbon footprint. This can include improvements in energy efficiency, the use of renewable energy sources, and the development of more sustainable production processes.

Overall, digital transformation in the aluminum production industry is leading to significant changes in manufacturing processes, including increased automation and data analytics, the use of advanced manufacturing technologies, and a focus on sustainability. These changes are helping manufacturers to improve efficiency, reduce costs, and meet the evolving needs of their customers. (Granstrand & Holgersson, 2020)

References

Adner, R., & Kapoor, R. (2010). Value creation in innovation ecosystems: how the structure of technological interdependence affects firm performance in new technology generations. *Strategic Management Journal*, *31*(3), 306-333. https://doi.org/10.1002/smj.821

AG, A. A. M. (2021). *Financial Report 2021*. https://www.amag-al4u.com/fileadmin/user_upload/Investor_Relations/Finanzen_und_Berichte/Geschaeftsberichte/2021/AMAG_Geschaeftsbericht_2021_Finanzbericht_Englisch.pdf

Aluminum, H. (n.d.). *Aluminum Smelting Industry Explained*. Retrieved December 22 from https://www.harboraluminum.com/en/smelting

Aluminum, I. (2022, 20 July 2022). *Primary Aluminum Production*. Retrieved August 14 from https://international-aluminium.org/statistics/primary-aluminium-production/

Areces, D. (2021a). Benefits of chemical composition analysis based on LP-LIBS in primary smelters. *International Aluminium Journal*, *97*. https://dte.ai/wp-content/uploads/2021/11/AIJ-DTE-Editorial-August-2021.pdf

Areces, D. (2021b). Performance optimization of aluminium furnaces based on real-time elemental analysis of the molten metal. *International Aluminium Journal*, *97*(5).

Arnoldi, M. (2020). Aluminium demand growth will soon outpace production growth. *Mining Weekly*. https://www.miningweekly.com/article/aluminium-demand-growth-will-soon-outpace-production-growth-2020-10-30/rep_id:3650

Association, T. A. (2021). *Primary Production 101*. Retrieved December 20 from https://www.aluminum.org/primary-production-101

Befesa. (2021). *Preserving natural systems* (ESG Report, Issue. https://images.befesa.com/media/2022/06/Befesa-ESG-Report-2021.pdf

Belingheri, P., & Neirotti, P. (2019). Digitalising products: towards an integrated view of challenges in development, design and user acceptance. *International Journal of Technology Management*, *80*(1-2), 1-11. https://doi.org/10.1504/ijtm.2019.099773

Benitez, G., Ayala, N., & Frank, A. (2020). Industry 4.0 innovation ecosystems: An evolutionary perspective on value cocreation. *International Journal of Production Economics*, *228*, 107735. https://doi.org/10.1016/j.ijpe.2020.107735

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, *3*(2), 77-101. https://doi.org/10.1191/1478088706qp063oa

Braun, V., & Clarke, V. (2012). Thematic analysis. In *APA handbook of research methods in psychology, Vol 2: Research designs: Quantitative, qualitative,* *neuropsychological, and biological.* (pp. 57-71). American Psychological Association. https://doi.org/10.1037/13620-004

Braun, V., & Clarke, V. (2021). One size fits all? What counts as quality practice in (reflexive) thematic analysis? *Qualitative Research in Psychology*, *18*(3), 328-352. https://doi.org/10.1080/14780887.2020.1769238

Brunetti, F., Matt, D. T., Bonfanti, A., De Longhi, A., Pedrini, G., & Orzes, G. (2020). Digital transformation challenges: strategies emerging from a multi-stakeholder approach. *The TQM Journal*, *32*(4), 697-724. https://doi.org/10.1108/TQM-12-2019-0309

Dolgikh, Y. A., Panfilova, E. S., & Smorodina, E. A. (2020). *Digital Technologies in Ensuring Financial Strength of Russian Non-Ferrous Smelters*. https://doi.org/10.2991/aebmr.k.200502.128

DTE. (2021a). *Our Solution*. Retrieved September 3 from https://dte.ai/our-solution/

DTE. (2021b). *Our Technology*. Retrieved September 7 from https://dte.ai/our-technology/

DTE. (2021c). *Our Value*. Retrieved September 3 from https://dte.ai/our-value/

DTE. (2021d). *Unlocking The Future of Metals*. Retrieved December 20 from https://dte.ai

EGA, E. G. A. P. (2020). *EGA 2020 Sustainability Report*. https://www.ega.ae/media/2617/ega-2020-sustainability-report.pdf

Granstrand, O., & Holgersson, M. (2020). Innovation ecosystems: A conceptual review and a new definition. *Technovation*, *90*. https://doi.org/10.1016/j.technovation.2019.102098

Gudmundsson, S. H., Matthiasson, J., Björnsson, B. M., Gudmundsson, H., & Leosson, K. (2019). Quantitative in-situ analysis of impurity elements in primary aluminum processing using laser-induced breakdown spectroscopy. *Spectrochimica Acta Part B: Atomic Spectroscopy*, *158*, 105646. https://doi.org/https://doi.org/10.1016/j.sab.2019.105646

Gudmundsson, S. H., Matthiasson, J., & Leosson, K. (2020). Quantification of trace elements in molten aluminum with randomized impurity concentrations using laser-induced breakdown spectroscopy. *OSA Continuum*, *3*(9), 2544-2552. https://doi.org/10.1364/OSAC.400430

Guo, Y., Zhu, W., Yang, Y., & Cheng, H. (2019). Carbon reduction potential based on life cycle assessment of China's aluminium industry-a perspective at the province level. *Journal of Cleaner Production*, *239*, 118004. https://doi.org/10.1016/j.jclepro.2019.118004

Gupta, A., & Basu, B. (2019). Sustainable Primary Aluminium Production: Technology Status and Future Opportunities. *Transactions of the Indian Institute of Metals*, *72*(8), 2135-2150. https://doi.org/10.1007/s12666-019-01699-9

Hydro. (2008, 2008). *HSE The Hydro Way The Handbook*. Retrieved December 9 from https://www.hydro.com/Document/Doc/HSE%20handbook?docId=3011

Kvande, H., & Drabløs, p. a. (2014). The Aluminum Smelting Process and Innovative Alternative Technologies. *Journal of occupational and environmental medicine / American College of Occupational and Environmental Medicine*, *56 Suppl 5S*, S23-S32. https://doi.org/10.1097/JOM.0000000000000062

Limited, C. H. G. (2021). *Environmental, Social And Governance Report*. http://en.hongqiaochina.com/Uploads/File/2022/05/30/E1378-ESG.20220530185231.pdf

Magistretti, S., Pham, C. T. A., & Dell'Era, C. (2021). Enlightening the dynamic capabilities of design thinking in fostering digital transformation. *Industrial Marketing Management*, *97*, 59-70. https://doi.org/https://doi.org/10.1016/j.indmarman.2021.06.014

Marciano, S., Mugnier, N., Clerin, P., Cristol, B., & Moulin, P. (2006). Nanofiltration of Bayer process solutions. *Journal of Membrane Science*, *281*(1-2), 260-267. https://doi.org/10.1016/j.memsci.2006.03.040

Matarazzo, M., Penco, L., Profumo, G., & Quaglia, R. (2021). Digital transformation and customer value creation in Made in Italy SMEs: A dynamic capabilities perspective. *Journal of Business Research*, *123*, 642-656. https://doi.org/10.1016/j.jbusres.2020.10.033

Matt, D. T., Molinaro, M., Orzes, G., & Pedrini, G. (2021). The role of innovation ecosystems in Industry 4.0 adoption. *Journal of Manufacturing Technology Management*. https://doi.org/10.1108/JMTM-04-2021-0119

Padamata, S. K., Yasinskiy, A., & Polyakov, P. (2021). A Review of Secondary Aluminum Production and Its Byproducts. *JOM*, *73*(9), 2603-2614. https://doi.org/10.1007/s11837-021-04802-y

Paraskevas, D., Kellens, K., Voorde, A. V. d., Dewulf, W., & Duflou, J. R. (2016). Environmental impact analysis of primary aluminium production at country level. *Procedia CIRP*, *40*, 209-213. https://doi.org/10.1016/j.procir.2016.01.104

Pawlek, R. (2022, July 20 2022). *Secondary Aluminum Producers*. Retrieved October 17 from https://www.lightmetalage.com/resources-section/secondary-producers/

Ralph, B., & Stockinger, M. (2020). *Digitalization and digital transformation in metal forming: key technologies, challenges and current developments of industry 4.0 applications*. Montanuniversität Leoben, Lehrstuhl für Umformtechnik.

RioTinto. (n.d.-a). *Potrooms*. Retrieved September 10 from https://www.riotinto.is/?PageID=115

RioTinto. (n.d.-b). *Production*. Retrieved December 20 from https://www.riotinto.is/?PageID=23

Rocha, C. F., Mamédio, D. F., & Quandt, C. O. (2019). Startups and the innovation ecosystem in Industry 4.0. *Technology Analysis & Strategic Management*, *31*(12), 1474-1487. https://doi.org/10.1080/09537325.2019.1628938

Rong, K., Hu, G., Lin, Y., Shi, Y., & Guo, L. (2015). Understanding business ecosystem using a 6C framework in Internet-of-Things-based sectors. *International Journal of Production Economics*, *159*, 41-55. https://doi.org/10.1016/j.ijpe.2014.09.003

Roser, C. (2017). *Industry 4.0 – What Works, What Doesn't*. Retrieved December 14 from https://www.allaboutlean.com/industry-4-0-potentials/

Rusal. (2021). *Sustainability Report*. https://rusal.ru/upload/iblock/501/40f8ubp92pobxuxf3yjardaihqd3otqk.pdf

Schoning, H. (2018). Industry 4.0. *It-Information Technology*, *60*(3), 121-123. https://doi.org/10.1515/itit-2018-0015

Sgouridis, S., Ali, M., Sleptchenko, A., Bouabid, A., & Ospina, G. (2021). Aluminum smelters in the energy transition: Optimal configuration and operation for renewable energy integration in high insolation regions. *Renewable Energy*, *180*, 937-953. https://doi.org/10.1016/j.renene.2021.08.080

Shirish, A., & Batuekueno, L. (2021). Technology renewal, user resistance, user adoption: status quo bias theory revisited. *Journal of Organizational Change Management*, *34*(5), 874-893. https://doi.org/10.1108/jocm-10-2020-0332

Sorger, M., Ralph, B. J., Hartl, K., Woschank, M., & Stockinger, M. (2021). Big Data in the Metal Processing Value Chain: A Systematic Digitalization Approach under Special Consideration of Standardization and SMEs. *Applied Sciences*, *11*(19), 9021. https://doi.org/10.3390/app11199021

Souza, A. M. F. d., Soares, F. M., Castro, M. A. G. d., Nagem, N. F., Bitencourt, A. H. d. J., Affonso, C. d. M., & Oliveira, R. C. L. d. (2019). Soft Sensors in the Primary Aluminum Production Process Based on Neural Networks Using Clustering Methods. *Sensors*, *19*(23), 5255. https://doi.org/10.3390/s19235255

Statista. (2021, April 2021). *The world's leading primary aluminum producing companies in 2020, based on production output*. Retrieved October 15 from https://www.statista.com/statistics/280920/largest-aluminum-companies-worldwide/

Striteska, M. K., & Prokop, V. (2020). Dynamic Innovation Strategy Model in Practice of Innovation Leaders and Followers in CEE Countries-A Prerequisite for Building Innovative Ecosystems. *Sustainability*, *12*(9), Article 3918. https://doi.org/10.3390/su12093918

Yin, R. K. (2003). *Case Study Research: Design and Methods* (3rd ed., Vol. 5). SAGE Publications.

Appendix A Semi-structured interview guideline (adopted from Benitez et al. (2020); Granstrand and Holgersson (2020))

1. Can you tell me if [Actor] been involved in any digital transformation projects in the aluminum industry? Could you tell me more about those projects?
2. How and where do those projects originate from?
3. Do you need to collaborate with any other firms or individuals in order to compensate a lack of knowledge or competence, in order to drive forward the project?
4. What is it that [Actor] is bringing to the table when developing a product or project in collaboration with others?
5. When working in collaboration with other players in product or project development, who is pulling the strings or orchestrating the work done in order to push forward the project.
6. Have you noticed any bottlenecks arising in the development of these projects?
7. Have any projects or collaborations risen through the research centers or universities?
8. Does government or legislation body come into play at any point in those projects?