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Enabling End-to-End Digital Information Flows Through Product-Process-Resource Models

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BY
IOAN-MATEI SARIVAN

DISSERTATION SUBMITTED 2023

AALBORG UNIVERSITY
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CV

From a very young age, the intense passion for technology drove Matei towards pursuing a STEM related higher education. Motivated by this passion, Matei has attended the Robotics BSc program at Aalborg University. The bachelor thesis, having as subject a smart phone application able to control and program industrial manipulators, yielded Matei's first peer-reviewed scientific contributions written in collaboration with the associated AAU group members and supervisor Prof. Casper Schou.

Freshly specialised in industrial robotics engineering, Matei continued pursuing an MSc in Manufacturing Technology at Aalborg University during which the focus has been widened to include a broader understanding on the technical part of a manufacturing systems and the connected operations. The MSc opened the opportunity for Matei to attend an internship at Mercedes-Benz AG, located at the ARENA2036 open innovation research platform in Stuttgart Germany. The master thesis, written at Mercedes-Benz AG, yielded another two peer-reviewed papers written in collaboration with supervisors Prof. Ole Madsen and Prof. Simon Bøgh.

During the education years, Matei has worked as software developer for AnyBody Technology A/S, where he matured his software development skills, skills which proved vital in all the academic projects he has been involved in. During the MSc studentship, Matei has also worked as a student assistant under the supervision of Ph.D. Mads Bejlegaard and in collaboration with Sjørring Maskinfabrik, part of Manufacturing Academy of Denmark (MADE DIGITAL).

The MADE DIGITAL project has later evolved into a MADE FAST Ph.D. project into which Matei embarked as a Ph.D. candidate in 2020 under the supervision of Prof. Brian Vejrum Wæhrens and Prof. Ole Madsen. During the Ph.D. years, Matei has investigated the impact of digital integration on operations conducted along the value chain at ETO companies by gathering empirical evidence based on specially developed digital tools, with a focus on the programming of welding robots. The theme of the project has proven to be of general interest in high-cost environments similar with Denmark, which led to a four months long research stay under the supervision of Prof. Olav Egeland, at NTNU in Trondheim, Norway.

ENGLISH SUMMARY

Small medium enterprises located in high-cost environments like Northern Europe, are increasing their reliance on digitalization and robotics to lower production costs and to keep the competitive edge over companies in low-cost environments. It is intended through this research project to challenge the traditional trade-off between the high degree of automation and flexibility. Both automation and flexibility are vital in the context of engineering-to-order (ETO) SMEs located in high-cost environments, that have a production system tending towards one-of-a-kind production. The focus is placed on companies that are mainly using welding as their primary production operation. Using and developing technological methods shows that a high degree of flexibility is kept by digitally integrating manual labour and ensuring seamless end-to-end information flow across the internal and downstream supply chains. This project seeks to create the theoretical fundament on which technological solutions can be developed to digitally integrate pre-production operations and production operations within a seamless one-piece information flow. Thus, the concept of a product-model is proposed which congregates the design, engineering, and pre-production information about the product itself and the manufacturing system, in the context of steel welding industry. The necessary research and development are conducted through several design science cycles to ensure both the relevance of the proposed concept for the studied case company, and the rigor of the contribution to the knowledge base in the field. It is intended through the implementation of product-model¬ based technologies to eliminate the need for manually conducted pre-production operations e.g., welding-robot programming, and radically reduce the time needed for pre-production operations. A direct consequence is expected to be an increase in usage of welding-robots while allowing ETO SMEs keep the level of flexibility which is naturally associated with their business model.

DANSK RESUME

Små mellemstore virksomheder beliggende i højomkostningsmiljøer som Nordeuropa øger deres afhængighed af digitalisering og robotteknologi for at sænke produktionsomkostningerne og for at bevare konkurrencefordele i forhold til virksomheder i lavprismiljøer. Det er hensigten gennem dette forskningsprojekt at udfordre den traditionelle afvejning mellem den høje grad af automatisering og fleksibilitet. Både automatisering og fleksibilitet er afgørende i forbindelse med engineering-to-order (ETO) SMV'er placeret i højomkostningsmiljøer, som har et produktionssystem, der tenderer mod enestående produktion. Fokus er placeret på virksomheder, der primært anvender svejsning som deres primære produktionsvirksomhed. Brug og udvikling af teknologiske metoder viser, at der opretholdes en høj grad af fleksibilitet ved digitalt at integrere manuelt arbejde og sikre problemfri end-to-end informationsflow på tværs af de interne og downstream forsyningskæder. Dette projekt søger at skabe det teoretiske grundlag, på hvilket teknologiske løsninger kan udvikles til digitalt at integrere præproduktionsoperationer og produktionsoperationer i et sømløst informationsflow i ét stykke. Således foreslås konceptet med en produktmodel, som samler design-, ingeniør- og præproduktionsinformation om selve produktet og fremstillingssystemet i forbindelse med stålsvejseindustrien. Den nødvendige forskning og udvikling udføres gennem flere designvidenskabelige cyklusser for at sikre både relevansen af det foreslåede koncept for den undersøgte casevirksomhed og stringens i bidraget til videnbasen på området. Det er beregnet til gennem implementering af produktmodel-baserede teknologier at eliminere behovet for manuelt udførte præproduktionsoperationer, f.eks. svejserobotprogrammering, og radikalt reducere den nødvendige tid til præproduktionsoperationer. En direkte konsekvens forventes at være en stigning i brugen af svejserobotter, samtidig med at ETO SMV'er kan bevare det fleksibilitetsniveau, som naturligt er forbundet med deres forretningsmodel.

ACKNOWLEDGEMENTS

I wish to express my warmest thanks to Professors Brian Vejrum Wæhrens and Ole Madsen for which I wear the deepest gratitude for the attentive guidance they have offered me during my Ph.D. study as supervisors. Alongside the excellent academic guidance, I was provided with much needed moral support and understanding, which greatly contributed towards completing my work as a Ph.D. student. Thank you, Professors, for all your encouragement, for all your support, and for believing in this work from the very start to finish!

This work would have not been possible without the funding received from the partners involved in MADE (Manufacturing Academy of Denmark), participants in the part-project WS 2.02, "Value chain digitalization and optimization": Sjørring Maskinfabrik, FORCE Technology and PDMTechnology, towards whom I want to express my gratitude. Thank you!

I want to thank all part-partners in this project and especially Sjørring which granted me unlimited access to their production line and offered me the necessary test objects to run the experiments. The willingness of the case-company to cooperate with the researcher is vital for the design science research methodology, and Sjørring went over and beyond to ensure it. I wish to mention Klaus Kalstrup, CEO; Morten Hvass, Project Manager; John Yde Hove, Project Manager; Andreas Kjær, Head of Supply Chain; Per Holst Menander, Development Engineer; Mads Fredsøe, Development Engineer, Jens Holm, Head of Production and finally, the work-shop workers who have conducted the fabrication of the experiment items. Thank you!

Thank you very much to Valk Welding who provided software license for Panasonic DTPS to prove the artefact works on Sjørring's production line. I wish to thank James de Villiers, Development Engineer, for help provided on the development side and Adriaan Broere, CTO for supporting and enthusiastically believing in this project! I also wish to thank RoboDK and DriveWorks for offering educational licenses for their software. Thank you to Migatronic Automation for providing the experimental setup used in this project composed of welding-robot and welding machinery and for the assistance they provided in setting everything up. Many thanks to Aalborg University for facilitating the development of this project by providing SolidWorks licenses and laboratory space to run the experiments.

The development made during this project would not have been as successful without the access granted by the Norwegian University of Science and Technology to their state-of-the-art robot-welding laboratories. I want to thank Professor Olav Egeland for hosting me at NTNU for the duration of my research stay and arranging access to the NTNU facilities. I also wish to thank Professor Andrei Lobov and Ph.D. Tuan

Ahn Tran for insight into their work which provided tremendous help in unlocking the enigmas of automatic programming of welding robots.

Last but not least, I want to thank my family and friends for their continuous support along these three long years. I want to express my deepest thanks to my partner, Alina, for supplying continuous moral support, understanding and patience, and helping me find strength to finish my work even in the hardest moments.

I kindly wish to dedicate this work to my grandparents, Ecaterina, and Nicolae, who have thought me to aim as high as possible and their ardent wish has always been to see their grandchildren succeed…

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PREFACE

Historians name the period of rapid economic growth, cultural and technological development met by the western aligned countries since the 17th century until the end of the 20th century as “The Western Miracle” (Rosenberg and Birdzell 1990). The Western Miracle stands at the base of the first three industrial revolutions and all their enablers. I will not go much into history, although I find the work made during this Ph.D. project highly aligned with many of the old principles which gave birth to our society as we know it today, where technology plays a major role in every comfort, we enjoy day by day. I will introduce however this paragraph from (Rosenberg and Birdzell 1990) here:

A fundamental factor holding together the Western science as an international enterprise was its adoption of a single standard of scientific truth based on observation, reason, experiment, and replicability. The standard enabled scientists to make use of findings from other laboratories, even from those in other disciplines. It also permitted artisans, merchants, manufacturers, and the rest of the working population to apply scientific discoveries to everyday labours.

What is presented in this Ph.D. thesis is merely a tiny drop in an ocean of knowledge, yet it is my great aspiration that this work will make a positive difference in the technological advancement of the Danish society.

Reader’s guide:

It is recommended for the papers to be read in the suggested sequence before reading this thesis. This thesis is based on a collection of four peer-reviewed papers which can be found at the end of this booklet.

LIST OF ABBREVIATIONS

Abbreviation	Meaning
AAU	Aalborg University
API	Application Programming Interface
CAD	Computer Aided Design
CIM	Computer Integrated Manufacturing
CNC	Computer Numerical Control
DSR	Design Science Research
DTPS	Desktop Programming Software
ETO	Engineering to Order
ISO	International Organization for Standardization
JSON	JavaScript Object Notation
KBE	Knowledge-Based Engineering
MADE	Manufacturing Academy of Denmark
MIG	Metal Inert Gas
MTO	Make to Order
NTNU	Norwegian University of Science and Technology
OLP	Offline Programming
PPR	Product-Process-Resource
RTO	Research and Technology Organization
SME	Small Medium Enterprise
STEP	Standard for Exchange of Product Data
UML	Unified Modelling Language
WISCON	Welding Interface for Steel Construction
XML	Extensible Markup Language

LIST OF PAPERS

1. THESIS CONTRIBUTIONS

Paper I - Bejlegaard, M., Sarivan, I.-M. and Waehrens, B.V. (2021), "The influence of digital technologies on supply chain coordination strategies", Journal of Global Operations and Strategic Sourcing, Vol. 14 No. 4, pp. 636-658. https://doi.org/10.1108/JGOSS-11-2019-0063

Paper II - Sarivan, IM., Madsen, O., Waehrens, B.V. (2022). Towards Automatic Welding-Robot Programming Based on Product Model. In: Towards Sustainable Customization: Bridging Smart Products and Manufacturing Systems. CARV MCPC 2021 2021. Lecture Notes in Mechanical Engineering. Springer, Cham. https://doi.org/10.1007/978-3-030-90700-6_19

Paper III - Sarivan, IM., Larsen, J.S., Madsen, O., Wæhrens, B.V. (2023). Elementary Welding Operations for Automatic Robot Programming. In: Kiefl, N., Wulle, F., Ackermann, C., Holder, D. (eds) Advances in Automotive Production Technology – Towards Software-Defined Manufacturing and Resilient Supply Chains. SCAP 2022. ARENA2036. Springer, Cham. https://doi.org/10.1007/978-3-031-27933-1_9

Paper IV - Ioan-Matei Sarivan, Ole Madsen, Brian Vejrum Wæhrens et al. Automatic Welding-Robot Programming Based on PPR Models, 03 October 2023, PREPRINT (Version 1) available at Research Square, https://doi.org/10.21203/rs.3.rs-3346143/v, submitted to International Journal of Advanced Manufacturing Technology (under review)

2. CONTRIBUTIONS ALONGSIDE DOCTORAL WORK

Paper I - Sarivan, IM., Schou, C., Madsen, O., Wæhrens, B.V. (2021). Smartwatch Integration in Digital Supply Chains. In: Dolgui, A., Bernard, A., Lemoine, D., von Cieminski, G., Romero, D. (eds) Advances in Production Management Systems. Artificial Intelligence for Sustainable and Resilient Production Systems. APMS 2021. IFIP Advances in Information and Communication Technology, vol 631. Springer, Cham. https://doi.org/10.1007/978-3-030-85902-2_7

Paper II - Simon Vestergaard Berg, Mette Busk Nielsen, Morten Svangren Bodilsen, Casper Schou, Ioan-Matei Sarivan, Automated Scheduled Nesting for Flexible Manufacturing, Procedia CIRP, Volume 107, 2022, Pages 1415-1420, ISSN 2212-8271, https://doi.org/10.1016/j.procir.2022.05.167

3. PREVIOUS CONTRIBUTIONS

Paper I - Sarivan, I. M., Batuev, A., Ciontos, A. E., Holtskog, O., Sivertsen, E., and Schou, C. (2018). Using Collaborative Robots as a Tool for Easier Programming of Industrial Robots. Memorias De Congresos UTP, 1(1), 201-211. Recuperado a partir de https://revistas.utp.ac.pa/index.php/memoutp/article/view/1916

Paper II - Andreea Ciontos, Ioan-Matei Sarivan, Casper Schou, Universal Industrial Interface - Mobile, Procedia Manufacturing, Volume 38, 2019, Pages 391-399, ISSN 2351-9789, https://doi.org/10.1016/j.promfg.2020.01.050

Paper III - I.-M. Sarivan, Johannes N. Greiner, D. Díez Álvarez, F. Euteneuer, M. Reichenbach, O. Madsen, S. Bøgh, Enabling Real-Time Quality Inspection in Smart Manufacturing Through Wearable Smart Devices and Deep Learning, Procedia Manufacturing, Volume 51, 2020, Pages 373-380, ISSN 2351-9789, https://doi.org/10.1016/j.promfg.2020.10.053

Paper IV - Sarivan, IM. et al. (2021). Deep Learning-Enabled Real Time In-Site Quality Inspection Based on Gesture Classification. In: Advances in Automotive Production Technology – Theory and Application. ARENA2036. Springer Vieweg, Berlin, Heidelberg. https://doi.org/10.1007/978-3-662-62962-8_26

Patent - Sarivan, I-M., Madsen, O., Euteneuer, F., Díez Alvarez, D., Baumann, S. A., and Schreiber, M. (2021). Verfahren zur Überprüfung mindestens eines durch eine Person durchgeführten manuellen Arbeitsschritts. (Patent No. DE102020006056A1). Deutsches Patent-und Markenamt.

CHAPTER 1. INTRODUCTION

The programming of welding robots is an extraordinarily complex and time-consuming task which currently, in order to be performed, it requires a wide range of resources in terms of technology, labour, and infrastructure. Traditionally, welding-robots are widely used in mass-manufacturing environments, where the economy of scale justifies the investment in these devices as they come with many advantages, among which (Epping and Zhang 2018):

- Increased safety for human labour, as the exposure to various gases and radiation is reduced or eliminated.
- Reduced production cost following an initial investment, a welding robot which functions non-stop is cheaper to operate than having a human welder.
- Uniform quality level across products, as welding robots are characterized by high repeatability and accuracy.
- Increased productivity, provided that the robot has little to no down time.

Overall, the main motivation behind using welding-robots is the ability to lower production cost at a level which renders the manufacturing company competitive in its market. However, the advantages of automating with welding-robots are overturned in one-of-a-kind production environments as the welding robots must be programmed often. To program a welding robot, a wide range of information is required regarding the product that is welded, and the process which produces the product (Lauridsen 1991). On one hand, the programming effort requires expensive resources and high investment in automation technologies and infrastructure. The return of investment can be negatively affected by a low utilization rate of these devices. On the other hand, limiting the company's product offering through standardization to enable automation may compromise flexibility and the competitive strategy of the company (Willner et al. 2016b). Companies which offer high product variety can therefore be reluctant towards using welding-robots to automate.

The work presented in this Ph.D. thesis revolves around the research and development made towards the end-to-end digital integration of the value chain to enable a seamless information flow, from product order to production, which makes possible the automatic programming of welding robots. The focus is placed on engineering-to-order (ETO) value chains of metal fabrication enterprises found in high-cost environments like Denmark. The tangible result of the work is a software artefact which is introduced, tested, and implemented at the case company which offers the empirical context of this research. Contributions to the research field's knowledge base are made under the form of the novel approach for using product-process-resource information for programming of welding robots and under the empirical findings on how novel digital technologies can retain advantages of both automation and flexibility on ETO value chains.

1.1. A BRIEF HISTORICAL CONTEXT

There is no doubt about the significance carried by the relationship between manufacturing and technology. Throughout history, technological advancements have heavily influenced and revolutionized manufacturing. The time periods when novel and disruptive technologies were widely and heavily adopted are named *industrial revolutions*. With the emergence of the third industrial revolution in the mid-1900s, the technological boom compelled up to 90% of the existing production assets to be replaced by new manufacturing technologies (Wee et al. 2015). Industrial robots and computer numerical control (CNC) machines replaced much of the human labour present in mass manufacturing setups, with advantages as faster throughput, steady quality levels, less hazard for human workers, and reduced production cost. Moreover, some of these programmable forms of automation enabled flexible manufacturing to a certain degree which can accommodate the production of a higher variety of items, although at a higher cost than a dedicated manufacturing system (Koren and Shpitalni 2010). The companies which were fast to adopt these new technologies, gathered a strong advantage over their competitors (Blois 1986).

In the 1980s, the promise of computer integrated manufacturing (CIM) was that manufacturing companies could achieve higher flexibility and high product mix, rapid response to market requirements, great control of the manufacturing process and low production cost, to name a few of the advantages (Blois 1986). However, in the 1990s and 2000s, the trend of offshoring emerged, where manufacturing enterprises could reap the benefits of manufacturing in a low-cost environment with a relatively low initial investment (compared to investing in flexible automation), conditioned by having the proper managerial capabilities and the ability to build global operational networks (Waehrens et al. 2015). In the last decade, the consequences of offshoring have become apparent, and the rapid economic growth in the low-cost countries where the production was offshored, have yielded new competitors for manufacturing companies located in high-cost environments (Colli 2020; Haleem et al. 2018). Another consequence of offshoring is the tipping point, as described by (Wæhrens et al. 2012), where the company begins to lose production knowledge. In the face of a competitor far away which offers a very low price for their product, the SME at home might not be safe anymore (Boer 2019).

As we progress through what is considered the fourth industrial revolution (Wee et al. 2015), just as we have seen several times in history before, access to disruptive technologies (Blois 1986) may enable enterprises in high-cost environments to solidify their competitive edge again. From a technology point of view, the fourth industrial revolution is characterized by the amalgamation of various technologies (Madsen et al. 2022c) which form a digital pipeline that enables end-to-end seamless information flow from product order to product delivery (Madsen et al. 2022a). The digital integration of systems across the whole value chain is identified by (Colli 2020) as an enabler of the fourth industrial revolution.

1.2. ETO AND DIGITAL MANUFACTURING TECHNOLOGIES

Manufacturing companies with engineering to order (ETO) value chains are characterised by a deep order penetration point and a long product lead time (Willner et al. 2014). Every customer order is treated as a new project and expensive engineering resources are allocated to create the best product design based on the customer's demands (Gosling et al. 2017). The long lead time specific to ETO accentuates the high production cost which is often associated with a low level of productivity (Slack et al. 2010). ETO enterprises located in high-cost environments like Denmark, rely on competitive aspects like delivery dependability, speed, quality, and product innovation (Sansone et al. 2020; Slack et al. 2010). Since production cost is an issue, companies located in high-cost environments must ensure that the other competitive dimensions are properly maintained to attract and retain customers (Sansone et al. 2020).

Lead time is influenced among other factors, by waste generated through long waiting times for a precedent process to be completed, and through processes which have an iterative nature, like the product design stage which is made in collaboration with the customer (Jünge et al. 2023). A trade-off is identified between satisfying customers through delivery dependability and allowing more customer interaction on the design process of the product (flexibility) (Gosling et al. 2017). With every product being unique, ETO companies must invest large amount of expensive engineering resources to create new product designs and to adjust the manufacturing system to produce the product. Traditionally, the high level of responsiveness and flexibility along the value chain is ensured through manual human input while compromising on production volume and cost (Hayes and Wheelwright 1979). Conversely, high production volume enabled by automation is associated with low product variety and flexibility, as showed in Figure 1.

While digital technologies can reduce the trade-off between automation and flexibility, the simple replacement of one piece of technology with a new one is not sufficient if not done in a systematic manner across the value chain (Madsen et al. 2022b; Ahmad et al. 2018). This issue is recurrent and has been pointed out by (Slack 1987), as it is observed that initiatives originally meant to improve the performance dimensions of the production system, target individual resources and processes rather than addressing the performance of the whole manufacturing system. The approach focused on individual resources causes the improvement initiatives have suboptimal results. Bhalla et al. point out in their literature review on ETO value chains, that the approach found in literature towards solving challenges associated with the ETO manufacturing systems, is often theoretically motivated and further research is encouraged to investigate the development and the implementations of feasible solutions which can reduce the lead time, waste, and costs in ETO contexts (Bhalla et al. 2023).

It is desired through the work presented in this thesis to conduct practical research and development, aligned with the encouragement made by Bhalla et al. towards solving the challenges faced by enterprises with an ETO value chain. Empirical findings are to be brought forward which support the hypothesis that novel digital technologies can enable automation without fully compromising the flexibility associated with an ETO value chain, as suggested on the first row in Figure 1.

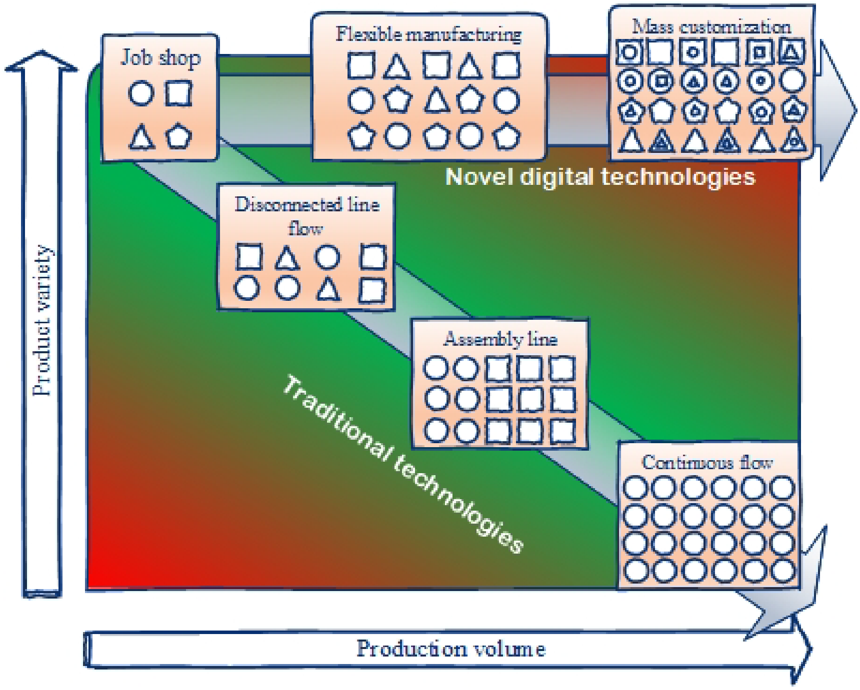


Figure 1: Traditionally, the relationship between the product and the production process is represented by the principal diagonal as suggested by (Hayes and Wheelwright 1979). Novel digital technologies have the ability of unlocking the benefits of both the flexibility associated with a disconnected line flow, and the productivity of an assembly line type of manufacturing system (Daft and Willmott 2020).

1.3. ETO AND PRODUCT DESIGN

The product design process is widely supported by some sort of computer aided design (CAD) system (Groover 2016). The CAD system is of particular importance in an ETO value chain as it allows for highly personalized products to be created by the product design engineers using a digital platform connected to knowledge data bases, allows the reusability of designs, collaborative work, and single-source-of-truth regarding product information (Quintero-Restrepo et al. 2018). The design process in an ETO enterprise usually starts with the recognition of need for a new product to be designed. The recognition is usually made by the sales manager of the ETO enterprise. As every order in an ETO context requires engineering resources, the interested customer together with the product design engineer and the sales manager define the application which will be satisfied by the product (the problem definition stage as showed in Figure 2) (Willner et al. 2014).

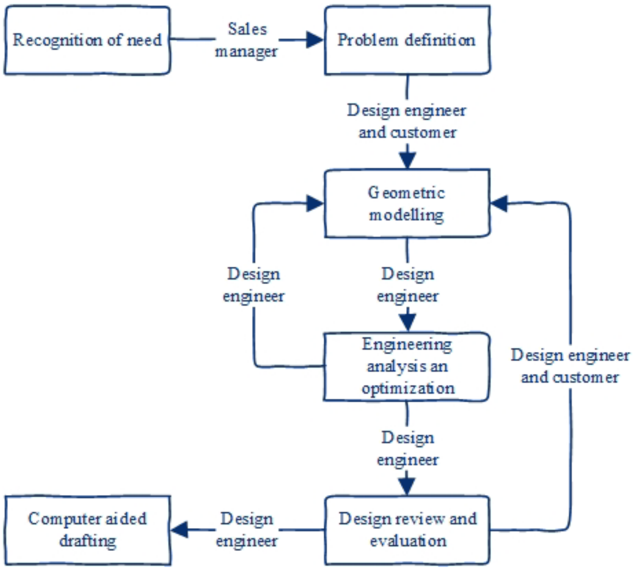


Figure 2: The design process at ETO enterprises using CAD. Adapted from (Groover 2016)

As it can be observed in Figure 2, once the application of the product is understood, the design engineer commences the computer aided design process by modelling the geometry of the product. This is an iterative process which contributes to the long lead time specific to ETO companies (Jünge et al. 2023). Moreover, the unknown number of iterations worsens the situation as it is not known beforehand how many iterations are enough to reach the customer's expectations. The design process involves both an internal stage, during which the design engineer analyses and optimizes in an implicit manner, and an external stage, during which the design engineer reaches out to the customer to ensure the viability of the design (Ulrich and Eppinger 2011; Willner et al. 2014). To evaluate the design together with the customer, the design engineer can use the virtual evaluation and virtual engineering tools available in the CAD system (Lee 1999a).

After the product design process is concluded by the design engineer and the customer, the resulted CAD model is documented using the computer aided drafting tools available in the CAD system which generate technical drawings (Lee 1999b). The technical drawings of the resulted CAD model include material specifications, bill of materials, manufacturing bill of materials and other documents that contain information which will guide the production engineers in setting up the production process and select production resources (Groover 2016). To set up a welding process based on design specifications, weld symbols are used in the technical documentation to pass information in a clear and concise manner from design engineer to welding engineer. The information contained in a weldment annotation is composed of the location of the weldment on the workpiece to be welded, the joint type of the weldment, the dimensions of the weldment, the welding process specification, and the weldment finish specification. An example of technical drawing with weldment annotations compliant with the ISO 2553:2019 standard is given in Figure 3. A weldment annotated with “a6⊾345<MIG”, is a fillet weldment with a throat dimension of 6mm, 345mm long and welded using the MIG welding process. The throat dimension is measured as the height of the triangle which fully inscribes the weldment.

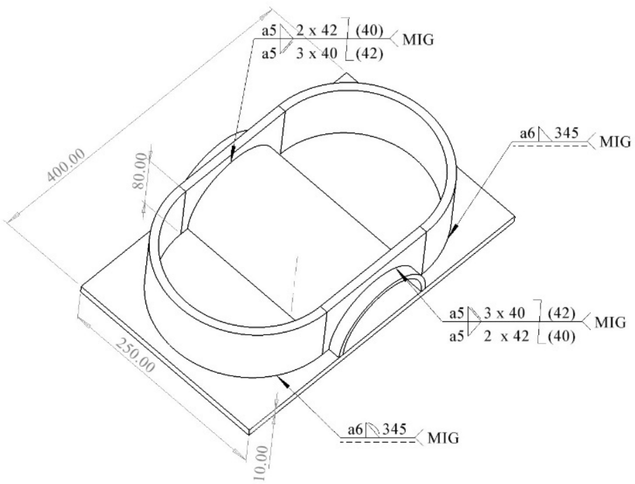


Figure 3: Technical drawing of workpiece to be welded which contains ISO 2553:2019 weldment annotations.

Modern CAD systems have available weldment design and annotations tools compliant with the ISO 2553 standard which allow the design engineer to properly document the design parameters of weldments directly on the 3D CAD model (Lombard 2018; Curtis Waguespack 2014; Siemens 2019a; Siemens 2019b; Dassault Systemes 2023a; PTC 2023; AutoDesk 2023). An example of a 3D CAD model annotated with weldments information is given in Figure 4. The weldment annotations are complemented by a 3D graphical representation of the actual weldment obtained following the welding process.

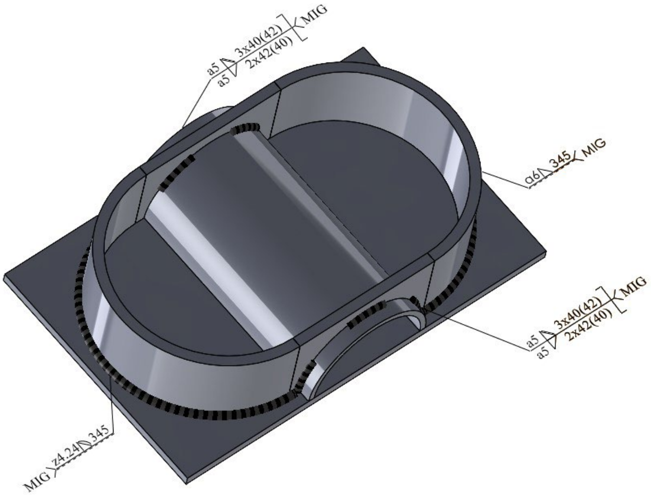


Figure 4: 3D CAD model with ISO 2553:2019 weldment annotations. The weldments are also graphically represented along the seams which must be welded. The model was created using the SolidWorks CAD system.

1.4. THE WELDING PROCESS

Welding is a metal fabrication process widely used in the manufacturing industry which involves heat to join two components of the same material, which yields a solid and durable engineering connection between the welded components called *weld joint.* A weld joint is composed of a *weld*, which can be a groove weld (if located between the two workpieces) or a fillet weld (if located alongside the workpieces), and a *joint* which can be a butt joint, a corner joint, a t-joint, a lap joint or an edge joint (Hughes 2009; Cary and Helzer 2004a). There are numerous welding and joining processes classified depending on the way energy (heat) is transferred to realize the weld. The welding process may use a filler material of the same type as the components which are welded (base material) – homogeneous welding, or a filler material different then the base material – heterogenous welding. The welding process which does not use filler material is named autogenous welding (Cary and Helzer 2004a). The work documented in this thesis is delimited to fillet welds obtained using homogenous arc welding for steel, more specifically, the metal-inert-gas process (MIG).

To prevent the chemical reaction between the puddle of molten metal and the gases which compose the atmosphere, the inert gas is used as a shielding gas which is pumped around the electrical arc and the welding puddle. The gas can be active, if it contains elements or compounds which are added intentionally to react with the welding puddle, or inert, if it is used only to shield the welding puddle from the surrounding atmosphere (Hughes 2009).

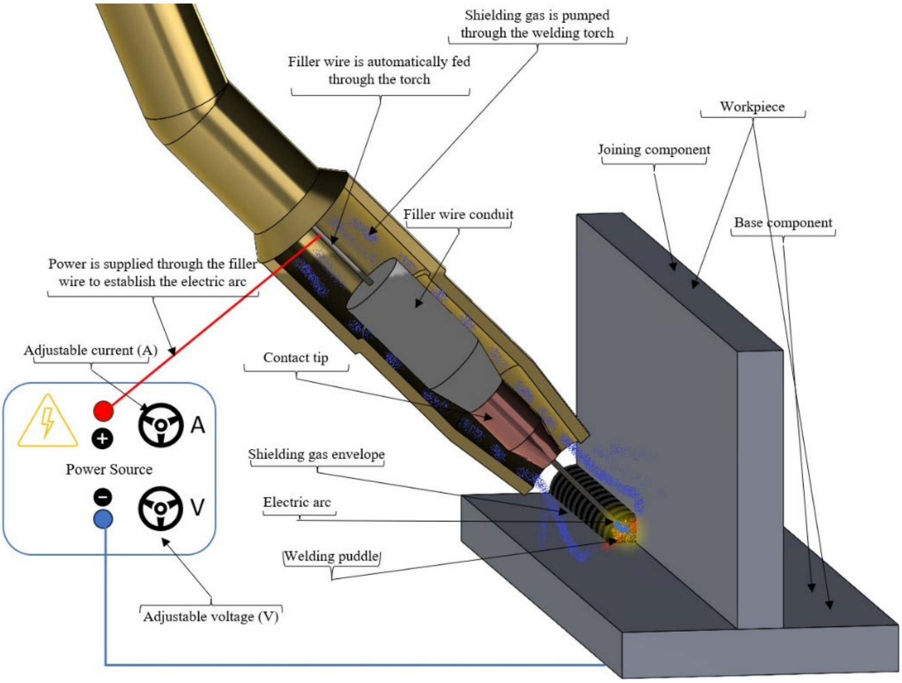


Figure 5: Representation of a MIG welding system's torch.

When using the MIG process, the welding system is composed of a power source, a wire feeding system, shielding gas supply, welding torch and workpiece. The power source delivers the electrical energy needed to establish the electric arc which generates the necessary heat and electro-magnetic forces to melt off the fed filler wire into a weld puddle to join the joining component and the base component. In Figure 5, a simplified representation of a MIG system is provided (Cary and Helzer 2004b). The energy input is controlled from the power source by adjusting the current and the voltage. Depending on the set voltage and current, the wire feed rate and the gas flow are automatically controlled by the welding machine, when an intelligent welding system is used (Wang et al. 2020). This is particularly valid for the welding machines which is used during this project. However, there are cases where the current intensity is adjusted based on the desired voltage and wire feed rate. A higher current setting is associated with a higher deposition rate of filler materials and a larger throat size. A high voltage setting is associated with a deeper penetration of the filler material into the workpiece. The throat size (A-mål) is one of the most basic quality criteria for a fillet weld joint (Jonsson et al. 2011) and it is specified in weldment annotations as presented in Figure 3 and Figure 4. In Figure 6, it is indicated how the weldment throat size is measured. Therefore, while welding, it is desired to control the deposition rate and the welding puddle in such manner that the specified throat size is achieved.

For a large throat size dimension, a high amount of material needs to be deposited which requires a high amount of input energy. Therefore, a single welding pass may not be sufficient to deposit all the needed filler material to obtain the required throat size. Moreover, setting a higher deposition rate and implicitly a higher energy input, can degrade the workpiece both in the heat-affected zone and across the workpiece due to thermal volumetric distortion (Messler 2019). Therefore, multiple passes are required to achieve the required throat size. Figure 6 contains a representation of a *multi-pass* weld joint.

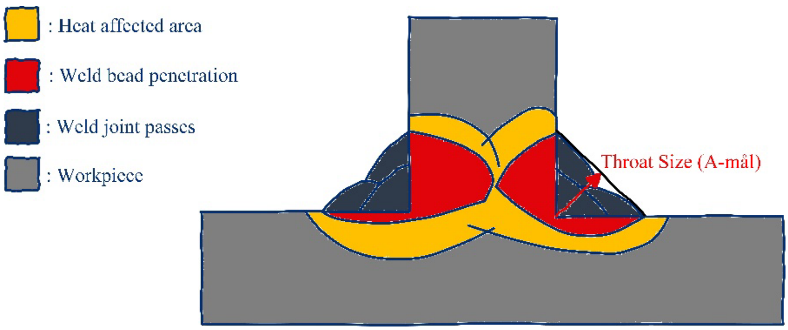


Figure 6: Representation of multi-pass welding with three passes on both sides of a T-joint. The throat size measurement is represented and annotated with A-mål.

To perform a welding process, the welding torch (showed in Figure 5) must be manipulated along the joint's seam as the electrical arc is active and filler wire is fed and deposited to the weldment joint. The manipulation of the welding torch (position and motion) can be performed using an industrial manipulator – welding-robot, after it is programmed to do so. The position of the welding torch relative to the joint seam is made by taking in consideration the distance between the torch's nozzle and the seam **S**, the welding angle **α**, and the travel angle **β** (Li et al. 2016). The distance **S** is also known as "stick-out" or "electrode extension" and it represents the exposed filler wire that comes out of the welding torch as it is fed and deposited during the welding process. The welding angle is measured between the base component and the torch, and the travel angle is measured between the joint seam and the torch. The stick-out, the welding angle and the travel angle are graphically represented in Figure 7.

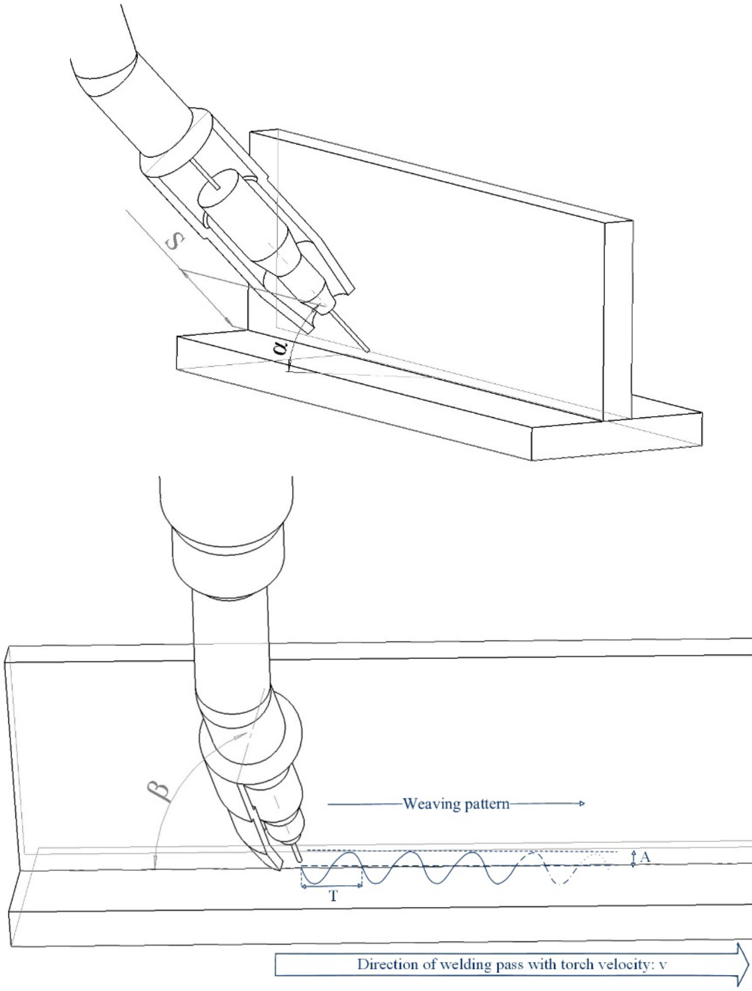


*Figure 7: Graphical representation of motion parameters. The stick-out **S** and the welding angle **α** are represented in the upper image. The travel angle **β** and the weaving parameters, amplitude **A** and period **T** are represented in the lower image.*

Depending on the deposition rate, the welding torch is moved along the weldment seam with a velocity **v**, also known as "torch travel speed." The motion can be linear or have an overlaid motion pattern. The motion pattern can be a zig-zag pattern, a rectangular pattern. A sinusoidal pattern with amplitude **A** and period **T** is represented in Figure 7. The overlaid motion pattern is also known as "weaving pattern."

A summary of all the necessary parameters needed to be considered when setting up a welding process is provided by (Lauridsen 1991) and are classified as shown in Figure 8. The weld design parameters are set by the design engineer together with the customer, as explained in section 1.3. The welding consumables are selected by the welding engineers. The motion parameters are programmed on the welding-robot, and the arc parameters are programmed on the welding apparatus.

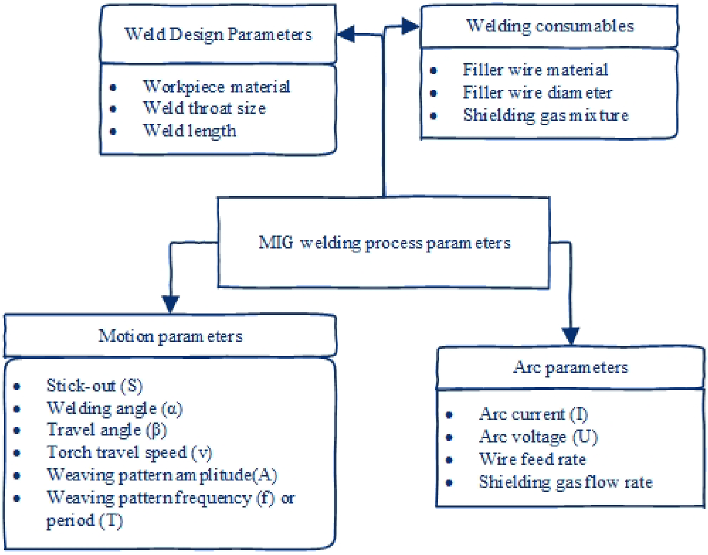


Figure 8: Classification of MIG welding process parameters adapted from (Lauridsen 1991)

1.5. PROGRAMMING OF WELDING ROBOTS

A welding-robot is a robotic manipulator of the welding torch which can conduct the welding process unsupervised after it is programmed. To program a welding robot, online and offline procedures can be used. Online programming is a very lengthy process, and it requires production to be stopped, as the welding engineer interacts directly with the welding-robot for duration of the programming (down-time). The main advantage of online programming is that the robotics engineer has full control over the manner the robot "behaves" as the program is executed and it can be ensured that there are no collisions with the workpiece, and the deviations between the CAD model of the product and the real product are addressed. The online programming is performed by using the teach-pendant or the human-machine interface available with the robot. Due to its lengthy nature and down-time of the welding robot, online programming methods are not preferred in environments where the robot must be programmed often.

Offline programming, as the name suggests, can be performed without stopping production and by using a personal computer on which an offline programming system (OLP) is available. The OLP software has available a digital representation of the welding cell and it benefits of the kinematics solvers available on the robot's controller which handles the computations necessary to transform positions from cartesian space to robot joint space (robot joint rotation angles or joint translation distances). The robotics engineer imports the CAD model of the product directly in the OLP system and places it relatively to the welding robot, as it is expected to be placed in the real welding-cell. Modern OLP systems have collision detection methods which helps in programming safe paths for the welding torch. Using CAD models and collision detection algorithms can potentially enable automatic programming of welding robots (Larkin et al. 2016).

A welding-robot program consists of a collection of goal points through which the welding torch must pass through to perform the welding process, together with instructions for the welding machine (the arc parameters as observed in Figure 8. The locations of the goal points are related to the locations of the weld joints across the CAD model of the product and the robotics engineer locates them by using the technical draft of the product. The orientation of the torch relative to the weld joint is set by using the stick-out, the welding angle and the travel angle. An example of a programmed goal point along the joint seam is given in Figure 9. The robotics engineer manually programs every welding goal point, the motion and position parameters and the arc parameters necessary to obtain the weld joint with the throat size specified in the technical draft of the product.

It can often happen that the real product that needs to be welded contains deviations and offset in its geometry due to distortions and fabrication errors, when compared with the CAD model. Therefore, cup-searching procedures are used to locate the item within the welding cell. The cup-searching procedure, as the name suggests, makes use of the welding torch's cup to accurately determine the position of the workpiece inside the welding cell. This is done by slowly moving the torch towards the workpiece until the cup touches the workpiece and the electrical circuit between the workpiece and the power source is close, but without establishing an electric arc (low energy is supplied in the circuit). As per the program, which is made using the OLP system, the difference between the location where the torch is expected to collide with the workpiece and the location where it collides with the workpiece is computed and then applied on all the target points which compose the welding program. An example of a three-dimensional cup searching procedure is showed in Figure 10.

The cup searching procedure is however valid only for deviations smaller than 15-20 millimetres and it cannot compensate for offsets within the weldment seam while welding. These offsets may happen while welding. Arc-sensing technology which uses online arc parameters measurements can however be used to overcome this challenge. Vision sensors can also be used in order to detect deviations greater than 15-20 millimetres.

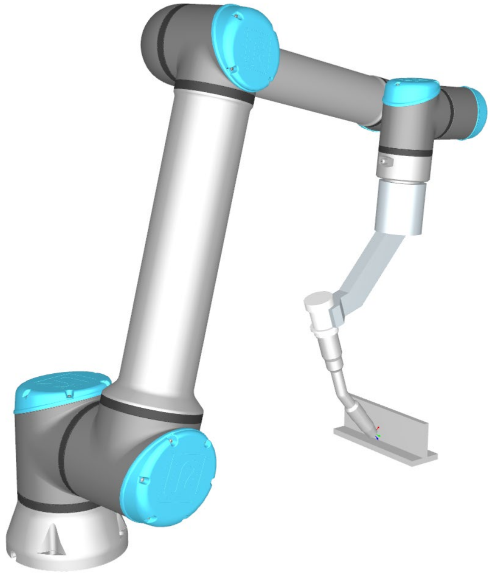


Figure 9: Example of programmed target point along the joint seam which the welding torch will pass through during the welding process (RoboDK OLP).

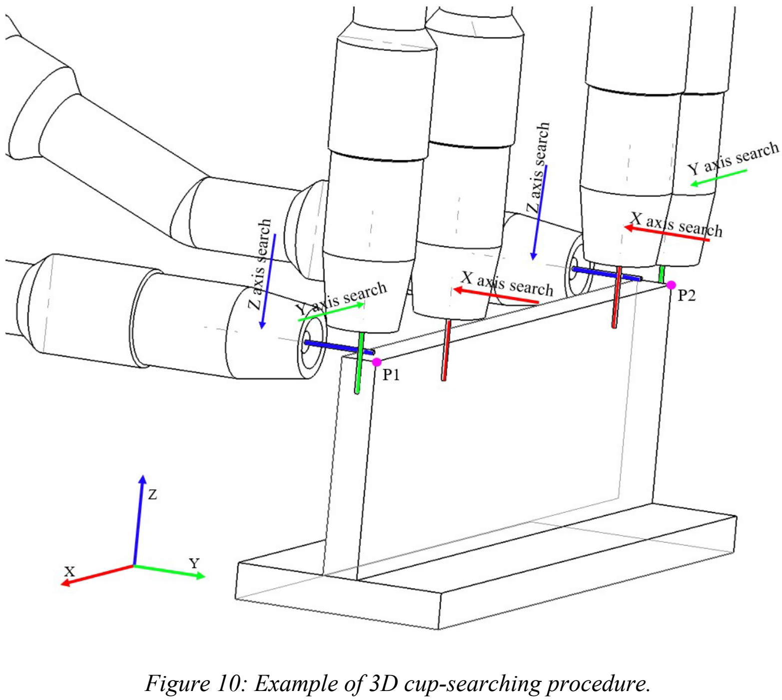


Figure 10: Example of 3D cup-searching procedure.

1.6. THESIS STRUCTURE

This thesis shapes the joint scope of the included four research papers which is based on and is set to serve as a binding structure between them. All four papers share a common research context, that of a company located in a high-cost environment, Denmark with an ETO value chain and involved in the metal fabrication industry. Details about the context and the case-company of the hereby presented research are given in Chapter 2.

The research design is presented in Chapter 3, where the research objective is formalized through research questions and details about the chosen research methodology are given. To be able to answer the research question, a literature state of the art is study is conducted, and the research gaps intended to be addressed are identified in Chapter 4.

Chapter 5 presents the way the research methodology was applied to develop the necessary technical artefacts which will be used to bring answers for the research questions. The chapter is structured in five sections, each section presenting a design cycle which yields results presented in each of the papers attached in this thesis.

A discussion which covers the theoretical and the practical implication of this work is given in the sixth chapter of the thesis. The final chapter concludes the work with final reflexions on the impact of novel digital technologies over the manner companies retain their competitive edge on a global market.

CHAPTER 2. RESEARCH CONTEXT

The research presented in this thesis was conducted in close collaboration with the Danish manufacturing industry in the context provided by Manufacturing Academy of Denmark (MADE). MADE is a non-profit organization composed of several Danish Universities, research and technology organizations and private companies involved in manufacturing. This research project was funded through MADE. MADE's mission is to bring together academia and industry with the purpose of conducting applied research which results in the development of new technologies and innovative solutions with high potential to be implemented at the case companies. MADE manages the research platform named "MADE FAST" (Flexible, Agile, Sustainable production enabled by Talented employees), which brings together five work streams which with the "Industry 4.0" and the reshoring agenda. The five work streams are "Sustainable manufacturing business models and value chain design", "Value chain execution and optimization", "Agile production systems", "Sustainable upscaling through digitalization of manufacturing process" and "Sustainable and agile workforce", each representing a work package within MADE FAST (www.made.dk).

As highlighted by McKinsey's study on "Danish manufacturing," the competition from low-cost environments is increasing. To keep the competitive edge, companies who operate in a high-cost environment like Denmark must invest continuously in new technologies and methods to reduce the production cost and to stay ahead of the competition through continuous innovation (McKinsey & Company 2016). Concerning the Danish metal fabrication industry, a shortage of skilled welders is being experienced which compels companies involved in this industry to rely more on automation (Sebastian Wittrock 2023). A real problem is therefore identified on how SMEs can cope with the pressure of automating production lines which are designed to be flexible and accommodate high variation in the product's design space – the context of the ETO value chain.

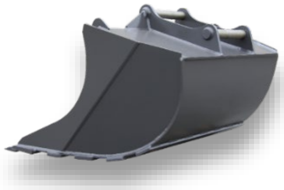
The research project was conducted as part of the "Value chain execution and optimization" work package which has as objectives the development of a robust IT infrastructure which enhances the efficiency of the value chain and reduces the operational and production costs of the company. The main objective of the package is to help the case companies in their digital transition towards flexible value chains able to cope with rapidly changing customer demands. The work conducted in this work package is meant to lay the foundations required to implement "Agile production systems", which is the theme of the third work package within MADE FAST which focuses on the development of flexible manufacturing solutions through robotics at the case companies. The case company participant in this research project was selected to be Sjørring Maskinfabrik A/S.

Sjørring Maskinfabrik A/S is an SME funded in 1946 and located in a small town with the same name, Sjørring, in the northern Denmark. Sjørring is involved in the metal fabrication industry, the main raw material for their products being metal sheets. The main production-floor fabrication operations being conducted at Sjørring are metal cutting, bending, drilling, welding, and sandblasting. The primary products sold are construction machinery attachments, wheel loader buckets and excavator shovels. With just under two hundred employees, Sjørring is the largest manufacturer of attachments for construction machinery in Europe. The company acts as a sub-supplier for the major producers of construction machinery acting as an original equipment manufacturer (OEM).

Figure 11: Excavator equipped with a shovel manufactured by Sjørring. Photo courtesy of Sjørring.

Sjørring has an engineer-to-order value chain, in which the customer is heavily involved in the design process of the products. The design of the bucket is highly dependent on the application and the material which is either dug through or transported. The buckets and the shovels are each classified in five different types, as it can be observed in Table 1. Every type has a large customization space in terms of volume, shape, attachments, thickness of plates, accessories, mechanical interface between it and the machine, and overall geometry. The demand of customized items is high because a proper design translates in considerable financial savings when it comes to the vehicle's fuel consumption and wear and tear components like tires and hydraulic systems. Sjørring sells up to 12000 construction vehicle attachments every year, among which there are over 1500 variants. Every time a new variant is required by the customer, a design engineer intervenes over the CAD model of the product. In order to satisfy the ever-increasing demand for high quality and highly customized products, Sjørring is continuously looking to optimise its operations and reduce the production cost in order to stay in front of the competition from low-cost areas.

Table 1: Examples from Sjørring's product offering. Images courtesy of Sjørring. Each of the displayed products can be up scaled and down scaled using product configurators.

Wheel loader buckets	**Excavator shovels**
General purpose bucket	General purpose shovel
	
High-dump bucket	Grading shovel
	
Rock bucket	Cable shovel
	
Light material bucket	Rock shovel
	
Mining bucket	Heavy-duty shovel
	

Since 2016, Sjørring Maskinfabrik has been going through a strategic change motivated by the need of increasing production capacity, lower production cost and use the human resources as efficiently as possible in an attempt of developing the business further. Therefore, Sjørring has joined the MADE program in order to access new knowledge and cutting-edge technologies as enablers.

The first stage of the collaboration with MADE was concerned with the development of a product configurator which makes it possible for low skilled personnel to generate product variations based on the customer's requirements. The results of this initiative are addressed in paper I attached to this thesis. More details about product configurators are given in section 5.1. Being satisfied with the results after implementing the product configuration on their value chain, Sjørring decided to further the collaboration with MADE and initiate the hereby Ph.D. thesis.

As the focus of the hereby Ph.D. thesis is on automatic programming of welding robots, Sjørring decided to invest in the modernization of their welding robot hardware and acquire new welding cells from Valk Welding, a technology supplier from the Netherlands.

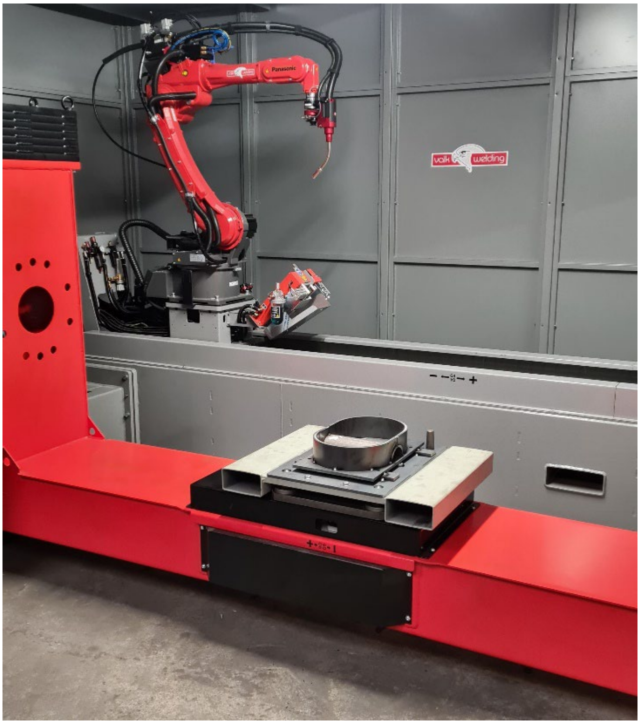


Figure 12: Panasonic welding robot supplied by Valk Welding. Welding setup located at Sjørring Maskinfabrik. The setup is equipped with a six-axis robotic manipulator for the welding torch and a two-axis positioner for the work piece.

CHAPTER 3. RESEARCH DESIGN

The process of creation is probably one of the most complex endeavours of the humankind. From an engineering perspective, the creation process is motivated by a societal need or a problem which needs to be addressed and reduced. The engineer applies scientific knowledge acquired through years of training and practical knowledge acquired through extensive experience during engineering activities (Hubka and Eder 1987). This knowledge becomes relevant for the society under the form of an "engineered solution." It can be said, in other words, that the engineer exploits the existent knowledge base to create a solution which addresses a problem or an issue relevant for the society and has a quantifiable and measurable impact (Nichols 1997). The knowledge base is expanded, in turn, through the methodical and rigorous process of "scientific research." Scientific research is the creative process through which scientists, motivated by curiosity and desire for novelty (Davis 1995), apply a scientific method to discover and evaluate new knowledge in a certain research field. The activity of the researcher is mostly concerned with the testing of hypotheses and the creation of a rigorous and reliable demonstration of their validity (Spier 1995).

Through this research project, it is intended to achieve a solid balance between relevance (associated with the engineering process) and rigour (associated with the scientific research process) in terms of outcome. It is, therefore, the aim of this work to both unlock new knowledge which brings novelty to the research field of automatic programming of welding robots and use that knowledge to solve a real problem identified at the case-company by developing a technical artefact. Empirical data and objective proof being at the very core of the work conducted, the researcher's stance may be declared to be positivistic. However, although the research approach is aligned with most of the five pillars of positivism: unity of scientific method, search for causal relationships, belief in empiricism, value-free science and the foundation of the research process is based on logic and mathematics (Hirschheim 1985), it will be found by the reader that this research cannot be value-free, as the associated *relevance* objective is to shape the surrounding world instead of only explaining it (Hevner and Chatterjee 2010b). As the knowledge generated through this research and documented in this research is meant to be used by an organization to better cope with the challenges met in its operational activity, the researcher's philosophical is declared as pragmatist (Goldkuhl 2012).

In the reminder of this chapter, the reader will be provided with details about the chosen research methodology. The reader will be guided through the research process and how the research method was applied to obtain the results which will be presented along the rest of the thesis. As this thesis is based on a collection of four research papers, the content of the research papers is briefly addressed, as they act as channels for knowledge dissemination which plays a significant role in chosen research methodology. Each paper addresses one of the proposed four research questions which act as catalyser for the research activity documented in the papers and summarized in this thesis.

3.1. RESEARCH METHODOLOGY – DESIGN SCIENCE RESEARCH

As stated in the introduction of this chapter, one of the objectives of the work documented in this thesis is to achieve balance between rigor and relevance. Therefore, the "design science research" (DSR) methodology was selected to conduct the research process (Hevner 2007). DSR implies focus on problem solving through use of technology and seeks as research outcome the creation of a technological artefact which positively impacts the organization where it is implemented and the people who will interact with it. DSR is an iterative research methodology, part of the information systems research framework. Upon adoption of DSR, the researcher strives towards achieving the best or most optimal solution for the identified problem (Hevner et al. 2004). The product of DSR, the artefact should solve an unsolved problem or solve an already solved problem in a more efficient or effective manner. The novelty of the artefact is the main element which distinguishes DSR from mere technical development of an IT artefact only by exploiting the existing knowledge base (engineering) (Hevner and Chatterjee 2010b). Therefore, just like any other research methodology, the purpose of DSR is to advance knowledge with utilitarian aims.

The DSR as research methodology like any other, implies a set of tools which are used to further the knowledge in the chosen research field and to synthesise new concepts in a tangible product (Nunamaker et al. 1990). Hevner's work "Three Cycle View of Design Science Research" is relied upon to design and structure the research process (Hevner 2007). Hevner distinguishes three iterative cycles the researcher goes through iteratively. These cycles are linked together, and every iteration brings the researcher closer to reaching the research objectives. The cycles are illustrated in Figure 13:

- The *Relevance Cycle* serves as a connection between the research context and the activity of the researcher. The research context has already been established in Chapter 2 of this thesis as the ETO SME located in a high-cost environment, Sjørring Maskinfabrik.
- The *Rigor Cycle* connects the activity of the researcher with the existing knowledge base which informs the research project, and it is expanded through the conducted research. In the case of this thesis, the primary selected knowledge base is the field of methods for automatic programming of welding robots.
- The *Design Cycle* is understood as the core activity of the researcher towards obtaining an artefact and it iterates between building it and evaluating it.

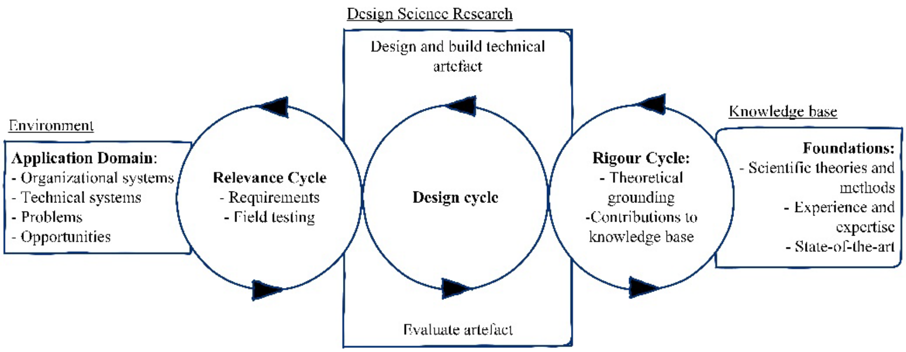


Figure 13: Representation of the design science research cycles as provided by (Hevner 2007)

3.2. HOW DESIGN SCIENCE RESEARCH IS USED IN THIS RESEARCH PROJECT

As stated by (Hevner 2007), the three cycles must be present in any DSR project for it to adhere to this methodology. To establish the relevance cycle, the context of the research project must be shaped. Background information about the context has already been provided for the reader in Chapter 2, however, a deeper understanding of the case-company is needed to properly identify the problem which will be treated during the research process and decide on what the best course of action is to develop a technical artefact. The first paper collected in this thesis (Bejlegaard et al. 2021), provides a detailed description of the strategic change which the case-company has been gone through in the recent years and a deeper view over the value chain of the company is provided in chapter 5. A set of requirements for the developed artefact are therefore set, based on which an evaluation will be made during field tests on the company's value chain.

The rigour cycle is established by identifying the knowledge base associated with the research field of automatic programming of welding robots and end-to-end digital integration of value chains. In the next chapter, the findings of the state-of-the-art study are provided for the reader, which represent the knowledge base this research is grounded in. The expertise of the robotics engineers and welding engineers at the case company also serves as part of the knowledge base and more information is given in chapter 4. The rigour cycle is fulfilled through the publishing of peer reviewed scientific contributions; the collection of four papers encapsulated in this thesis and conference presentations.

The design cycle is conducted by the researcher in an ongoing basis while exploiting the knowledge base to design and develop the artefact and evaluate it by ensuring the requirements set are being met. The activity of the researcher associated with the design cycle was sustained through two weeks long development sprints concluded with meetings with the case company and with the research supervisors to communicate the findings and decide upon further action. The bi-weekly meetings have served as “evaluation” stage, part of the design cycle’s iterations as observed in Figure 13. During the design cycle conducted in this project, the researcher has participated in a research stay at the Norwegian University of Science and Technology (NTNU) where access to state-of-the-art welding laboratory and equipment facilitated the deployment of the artefact on real production hardware. The researcher has delegated research and development tasks to B.Sc. of Mechanical Engineering (Johansen et al. 2023) and M.Sc. of Manufacturing Technology (Endelt et al. 2023) students to fulfil several of the artefact requirements. The findings made by the students are referred to in chapter 5 as they become part of the developed artefact.

3.3. RESEARCH QUESTIONS AND DESIGN SCIENCE CYCLES

The iterative nature of DSR (Hevner 2007) is made apparent in this work through four iterations at the level of the relevance and rigor cycles. As stated before, the design cycle was conducted on an ongoing basis, each iteration being defined by two weeks-long sprints concluded with a meeting between partners. During the design cycles the researcher used the findings made at the case-company, the knowledge base and own experience to conduct the research and the development required to come up with a solution for the problems identified at the case company. The four iterations of the relevance cycle each started by setting an initial set of requirements together with the case-company. At the end of the relevance cycles, the solution developed during the design iterations is field-tested either in the laboratory or at the case-company. The rigour cycle’s iterations were conducted by identifying the research gap in the knowledge base, motivated by the requirements set in the relevance cycle. Each rigour iteration was concluded with a scientific publication which summarizes the technical progress made during the design cycles and the induction process through which the proposed theoretical concepts are obtained. The research questions set for this Ph.D. project are summarised together with the DSR cycles in Table 2.

Table 2: Table with details on how the DSR cycles were used in this research work.

Design Science Research Cycles		
Relevance Cycle		
Iteration	Requirements	Evaluation Results
1	1) Identify and implement novel technologies which have the potential to optimize the value chain at the case company. 2) Reduce the time and resources needed for a new product variant to be engineered. 3) Identify opportunities for digital technologies implementation which will further reduce the lead time.	1) Product configuration wizards radically optimized the value chain of the case-company. 2) The engineering time was reduced from days to minutes and new business potentials were unlocked by reallocating resources. 3) A new bottle neck was identified at the level of welding-robot programming.
2	1) Identify particularities in the case company's value chain which can allow the deployment of digital technologies for automatic programming of welding-robots. 2) Develop a prototype which proves that automatic programming of welding robots is possible.	1) It was identified that the case-company's engineers insert welding annotations in CAD models compliant with the ISO 2553 standard. 2) A prototype was developed which proves that data can be extracted from ISO 2553 compliant CAD models, which can be sent further down the value chain to automatically program welding-robots.
3	1) Determine how can complex weldment geometries can be extracted and handled from CAD models and then imported in offline programming systems. 2) Design a proper data format for all the information necessary to program a welding robot and a welding machine to be stored in. 3) Determine the mathematical methods which allow for proper alignment of welding-torch along the weldment seam.	1) The weldment is discretised down to prismatic, quasi-stationary elements by making use of the tessellation points which constitute a weldment seam in the CAD environment. 2) The information necessary to program a welding-robot is stored under the form of "elementary welding operations". 3) The torch can be properly aligned along the weldment seam by using Horn's method for absolute orientation.
4	1) Establish an end-to-end digital pipeline for information flow across	1) Through experiments at the case-company, it was determined that the

<table>
<tr><td></td><td>the sales, engineering and pre-production operations which enables automatic programming of welding robots directly based on the customer's product specifications.
2) Radically decrease human input and time associated with the programming of welding-robots.</td><td>end-to-end digital pipeline for automatic programming of welding robots is indeed feasible. The weldments obtained using the automatically programmed welding-robots have been checked and classified by FORCE Technology in the required quality class.
2) It was determined that a new robot program can be generated in a few minutes instead of days.</td></tr>
<tr><td colspan="3">Design cycle</td></tr>
<tr><td colspan="3">The design cycle was conducted in this project on an ongoing basis with two weeks long sprints concluded with meetings together with the Ph.D. project supervisors and the case-company. Approximately seventy sprints were conducted which were complemented by visits at the case company, collaborations with.</td></tr>
<tr><td colspan="3">Rigour cycle</td></tr>
<tr><td>Iteration</td><td><u>Research Question</u></td><td>Publication</td></tr>
<tr><td>1</td><td>"How novel technologies facilitate the revoking of traditional trade-offs between high responsiveness and high efficiency while handling high product variety, and how will this affect downstream supply chain coordination?" - (Bejlegaard et al. 2021)</td><td>"The influence of digital technologies on supply chain coordination strategies", (Bejlegaard et al. 2021)</td></tr>
<tr><td>2</td><td>How can the welding-robot utilisation rate be increased in ETO production setups by using product models, to reduce product lead time without sacrificing flexibility?</td><td>"Towards Automatic Welding-Robot Programming Based on Product Model", (Sarivan et al. 2022)</td></tr>
<tr><td>3</td><td>What data structure can be used to contain all the necessary information to program a welding-robot without compromising on the weldment's quality?</td><td>"Elementary Welding Operations for Automatic Robot Programming", (Sarivan et al. 2023a)</td></tr>
<tr><td>4</td><td>How can the value chain ETO enterprises be digitalised to allow end-to-end information flow for automatic programming of welding-robots by making use of product-process-resource models?</td><td>"Automatic Welding-Robot Programming Based on PPR Models," (Sarivan et al. 2023b)</td></tr>
</table>

CHAPTER 4. KNOWLEDGE BASE ESTABLISHMENT

To conduct the design science research process, the knowledge base will be established. The knowledge base will be used as foundation for the research and artefact development process as it contains constructs, models, methods, and instantiations of theory which will serve as background of innovation. At the same time, the knowledge base can serve as supporting scaffold for evaluating the research results. By documenting and structuring the work under the form of the scientific publications which were collected in this thesis, contributions are made to the knowledge base, thus fulfilling the rigour cycle of DSR (Hevner and Chatterjee 2010a).

The knowledge base of this work is established in this chapter by conducting a state-of-the-art study within the extant literature in the field of automatic programming of welding-robots, product-process-resource models and digitalisation and automation of ETO value chains. The knowledge base is then augmented with findings and observations made at the case-company and with interviews with experts in the industry of welding-robots programming. A structured overview of this chapter is given in Figure 14.

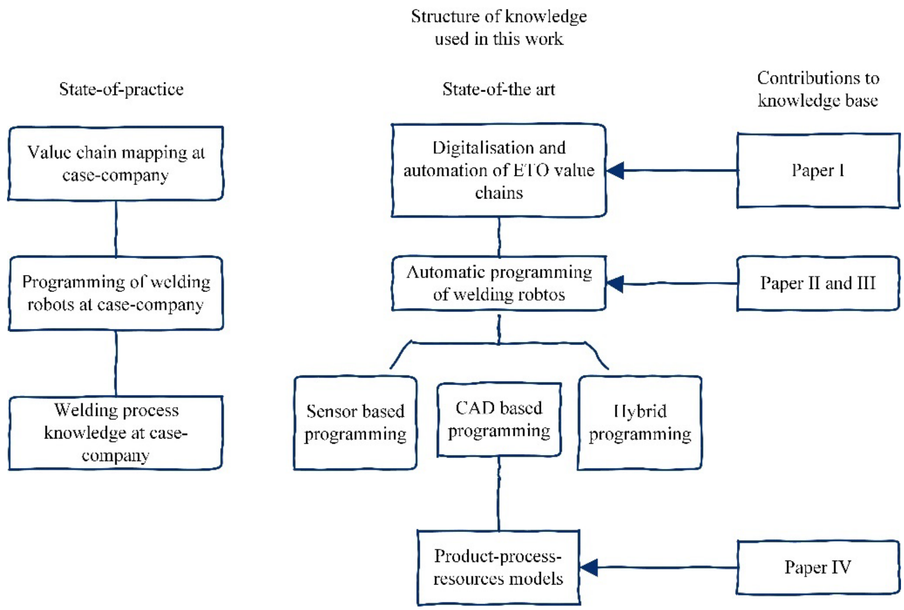


Figure 14: Structure of the knowledge base as it will be presented in this chapter.

4.1. STATE-OF-THE-ART

The identification of the knowledge base through state-of-the-art study is done in an exploratory manner by using several online and offline scientific data bases i.e., Google Scholar, Scopus and Aalborg University Library. The main key words used in the search of materials are ETO value chain optimisation, ETO value chain digitalization, engineering process automation, product design automation, welding robots, automatic programming of robots, automatic programming of welding robots, CAD-based programming of welding robots, product model-based programming of welding robots, welding process, automatic setup of welding process based on product data, integration of product-process-resource information, digital integration of product-process-resource data. A summary of the findings relevant for the design cycle are given together with information about the identified research gap which is intended to be closed through the rigor cycle. Some of the findings made in the literature are reiterated from the papers included in this Ph.D. thesis.

4.1.1. DIGITALIZATION AND AUTOMATION OF ETO VALUE CHAINS

In an ETO value chain, the customer's order penetrates the design phase, each order becoming a new project requiring expensive engineering resources (Gosling and Naim 2009), therefore flexibility and responsiveness to customer's needs is important. (Willner et al. 2016a) state that companies with an ETO value chain can benefit from automation initiatives just as well as companies with repetitive tasks. The maturity model proposed by (Willner et al. 2016a) serves as a strategic roadmap which practitioners can follow to achieve full automation of design on ETO value chain, which in practice converts brings the ETO value chain closer to an MTO value chain. This transition towards MTO is supported by technological implementations which automate the activity of engineer e.g., product configuration based on customer demands. While strategic roadmaps help in aligning the governance, the competences and the manner digitalization is used to create value in the company, a clear view on the available technology and inter-operation connectivity inside the company can help create a technological roadmap towards the automation of the value chain (Colli et al. 2019).

As the name "ETO" suggests, engineering operations are key for this kind of value chain. (Wikner and Rudberg 2005) suggest that engineering operations should be in the focus of optimization initiatives in an ETO context before focusing such initiatives on the production environment. ETO enterprises have a relatively high digital maturity when it comes to engineering technology and competences due to usage of advanced CAD tools (Strandhagen et al. 2018). Therefore, many digitalization and automation initiatives found in literature are focused on the product design operations and methods on how to digitalize the knowledge of the engineers to be easily reused or easily modified (Amadori et al. 2012). A common method to digitalize the product design operation is by using knowledge-based engineering (KBE) models, which if attached to the template of a product, they support rapid upscaling and downscaling of the product based on various design parameters (Chapman and Pinfold 1999). As noticed in the literature review conducted by (Fang and Wei 2020), alongside KBE models, the implementation of product configurators represents the focus of many initiatives for ETO value chain automation as they reduce lead time, the number of human resources needed to perform the engineering operations and fewer errors (Haug et al. 2012). (Haug et al. 2009) suggest that automation of engineering operations through e.g., product configurators enable the transitions of the ETO enterprises towards mass customization [1].

A knowledge base is established from the sources presented above on how strategic and technical roadmaps can be developed for the automation of the engineering operations at ETO enterprises through product configurators. A research gap is however identified regarding the impact made by the implementation of product configurators on downstream ETO operations e.g., production preparation and production. Paper I (Bejlegaard et al. 2021) seeks to fill this research gap through the study of an ETO value chain after a product configurator was implanted and it was found that a new bottleneck is formed, namely at the level of programming of welding robots.

4.1.2. AUTOMATIC PROGRAMMING OF WELDING ROBOTS

The knowledge base in the field of automatic programming of welding robots has also been established in Paper II – Paper IV of this thesis, therefore a summary will be provided in this subsection to give the reader context for the identified research gaps in the studied literature. Through automatic programming of welding-robots it is understood the process through which a welding-robot is set up to weld a workpiece with geometry which was not seen before without the need for manual intervention on the program which is running on the robot (Lauridsen 1991). This can be achieved in three ways, through sensor-based programming, CAD-based programming, or hybrid programming (Zych 2021).

[1] (Haug et al. 2009) draw an interesting parallel between the transition of ETO enterprises towards mass customization and the transition of mass producers towards mass customization. While ETO enterprises are experts along the product customization dimension, mass producers have expertise along the product standardization dimension.

Sensor-based programming of welding-robots

In sensor-based programming of welding-robots, sensors are used to detect and measure the workpiece, and determine the location of the welding seam (Madsen 1992). There are several sub-activities during the welding process in which sensors can be applied:

- Workpiece detection and localization: the workpiece's position and orientation (pose) within the welding cell is determined automatically (Schleth et al. 2018). Contact-based workpiece pose-determination is conducted by slowly moving the welding torch towards the workpiece until the welding torch collides with the workpiece. Based on the collision points, the workpiece's position is computed (Bickendorf 2014). This method is detailed in Figure 10, in section 1.5. Contact-free methods involve the use of optical or acoustic sensors to determine the position and orientation of the workpiece. Although plenty of literature documents the usage of contact-free methods for localization of object in bin-picking applications, a research gap is identified when it comes to how these sensors can be automatically programmed to detect a workpiece which was never been "seen" before (Schleth et al. 2018).
- Weld seam detection and localization: the weld-seam to be welded is detected by using contact or contactless methods (Rout et al. 2019). Just like in the case of contact-based methods for workpiece localization, collision detection between the welding torch and the workpiece is used at the level of the weld seam. Contactless methods for weld seam localization which generally involve vision sensors (cameras) (Yang et al. 2021; Rout et al. 2022) or vision sensors in combination with laser projections (Xu and Wang 2021). With this method, once the torch is aligned with weld seam, the torch "follows" the weld seam while it welds without the need of prior information.
- Adaptive welding allows for automatic alteration of the welding-robot's program in order to compensate for possible deviations along the weld seam due to metal warping or other causes. The most common adaptive welding method used is the arc-sensing method, where the arc's parameters (current and voltage) are probed with a high frequency to determine if the torch's trajectory deviates along the welding seam (Bai et al. 2017). Other methods for adaptive welding make use of vision sensors, ultrasound sensors and infrared sensors to determine and compensate in case of weld path deviations (Zhang et al. 2021).

Sensor-based programming of welding robots provides a good solution for solving uncertainty when it comes to differences between the CAD model and the real, physical product. These uncertainties often appear due to fabrication errors or the way the material responds under various factors of stress, e.g., heat input while welding. However, it is not clear from the study literature if sensor-based programming of welding robots is sufficient to weld an item on which multiple weldments are located in various regions around the item. That information can however be extracted from the CAD-model of the item.

CAD-based programming of welding-robots

CAD-based programming of welding-robots is the method through which the CAD model's geometry is directly used as a basis to generate welding-robot programs. There are two main approaches distinguishable in the literature towards CAD based programming: feature recognition and based on knowledge-based engineering (KBE) models.

Feature recognition methods for CAD-based programming are very similar with the way CAD models are sliced for additive manufacturing purposes e.g., 3DPrinting (Tran et al. 2022). (Legoff and Hascoet 1998) are using a feature extraction method based on calculations of surface normals, surface intersections and tangents, from which the weldment type and geometry is inferred. The emergence of the "standard for the exchange of product model data" (STEP), ISO 10303, enables feature recognition algorithms to directly access the geometrical elements of the CAD models by accessing the hierarchical structure provisioned by the STEP format allows the detection of intersections between solid bodies (Tran et al. 2021; Kiani and Saeed 2019; Kuss et al. 2017). Any CAD model, no matter what the CAD system which it was developed in is, can be converted into the STEP format. (Xuan and Ngoc 2020) use the STEP format to access the parameters of the CAD model's constituent components like points, edges, surfaces, and other properties and then specially developed algorithms are used to determine the possible location of a weldment seam, for example, the common edge between two surfaces.

CAD-based programming of welding-robots using KBE models make use of knowledge overlaid on top of the traditional CAD model, which is merely a geometric representation of the product. KBE models extend the use of CAD beyond 3D visualization by capturing process data required to configure the manufacturing process for the product (Prescott et al. 2020). Various approaches are identified in literature towards overlaying knowledge-based engineering about weldments on CAD models, many of which use the STEP file format to do so. (Berns and Verl 2014) use WISCON (welding interface for steel construction) files alongside step files to mark the locations of the weldments, information which is picked up by the offline programming system to automatically generate the welding-robot program. Another approach found recurrently in literature is that of using specially designed software for the engineers to manually select the locations of the weldments which normally are located along the intersection between two surfaces. This is not necessarily a fully automatic method to program welding robots as further input is required to "de-select" weldments which are not desired. Specially developed software then ensures that the whole geometry of the weldment seam is registered to properly program the welding robot (Larkin et al. Jul 2016; Bedaka and Lin Aug 2020; Liu et al. 2010). (Tran et al. 2023) use the tools readily available in the Siemens NX software (Siemens 2019a) for overlaying weldment design data to determine the position and the geometry of the weldment. Regardless of the method used to determine the position and the geometry of the weldment from CAD models, the result is used to automatically program the welding-robots by exploiting the collision detection and path planning algorithms available in the modern OLP systems (RoboDK 2023; Valk Welding 2023).

It is determined from the literature study in the field of automatic programming of welding robots based on CAD models, that the field is reasonably matured and there is a wide range of approaches on how CAD based programming of welding robots can be performed. However, only one example was found where information about the weldments readily available alongside CAD weldments was found: (Tran et al. 2023). Moreover, many modern CAD systems are compliant with the ISO 2553 standard which covers the way CAD models must be annotated with weldment information (Sarivan et al. 2023b). Therefore, a research gap is identified on how ISO 2553 compliant annotations can be used for automatic programming of welding robots. (Sarivan et al. 2022; Sarivan et al. 2023a) provide a thorough investigation on how these annotations can be used to program welding robots.

Hybrid programming of welding robots

As the name suggests, hybrid programming of welding robots is a combination of sensor-based and CAD-based programming of welding robots. CAD-based methods allow the automatic programming of the welding-robot based on the geometry of the product and on the process, knowledge overlaid on top of the CAD model. Given the fact that the real workpiece cannot be a one-to-one physical counterpart of the CAD model due to fabrication errors of any sort, sensor-based programming is used to adjust the CAD-based generate program to fit the geometry of the "real," physical product. The approach described by (Zheng et al. 2022; Galindo et al. 2018) makes use of technologies and methodologies for both CAD based and sensor-based welding-robot programming to obtain an accurate program for welding the products. In this manner, the benefits of both approaches are unlocked, but at the same time, also the challenges found for each of the methods before are inherited and it is not clear from the researched literature is ISO 2553 annotations can improve the hybrid programming of welding robots.

4.1.3. PRODUCT-PROCESS-RESOURCE MODELS

As stated in the previous subsection, modern CAD systems allows process data to be overlaid on top of the mere geometric CAD model. This approach has the potential to be enhanced by adopting the product-process-resource perspective over the information required to design and manufacture a product, where the product is realized by a process which uses resources. Resources can be understood as technological resources which are non-consumables and materials resources which are consumables (Fechter et al. 2018). In other words, together with the digital entity which reflects the product to be built, information can be added on how the product can be manufactured and what is needed for a product to be manufactured. (Ahmad et al. 2018) provide a thorough description of each element in the PPR perspective in the context of manufacturing:

- **Product domain:** has at its root the product family which is composed of product variants. Each product variant has an afferent assembly composed of components between which certain relationships are defined. These relationships can be understood as engineering connections between two or more components. In the case of a welded product, between two components there exists a weldment seam, therefore, the components are fixed to each other. Products can be further customized by adding features.
- **Process domain:** a process is required to realize the product. The process goes through individual states which can be configured to obtain the required relationship between two components. E.g., in the case of a welded product, certain power input is necessary to obtain the required weldment.
- **Resource domain:** the resource domain refers to the capabilities of the manufacturing system to support the manufacturing process. For example, in the case of a welded product, it is necessary to ensure that the welding apparatus can deliver the necessary power input to weld metal plates of certain thickness, while the welding-robot can reach all the weldment seams needed to be welded.

The PPR perspective offers a comprehensive overview on both the flow of materials and the flow of information across the value chain, thus mapping the requirements needed to manufacture products (Brecher et al. 2018). The PPR framework has been successfully implemented in several assembly production lines, the consequences being reduction of complexity and reusability of knowledge and models from on product variant to another (Pfrommer et al. 2013; Agyapong-Kodua et al. 2014; Ferrer et al. 2015; Schleipen and Drath 2009). However, it is not clear whether the PPR perspective can successfully be used for welding applications too. Therefore, (Sarivan et al. 2023b) propose a novel framework where the PPR perspective is instrumental in achieving an end-to-end digital pipeline from product design to automatic programming of welding robots.

4.1.4. STATE-OF-THE-ART FINDINGS

A state-of-the-art study was conducted to establish the knowledge gap within the field's literature and research the related work which can be used to successfully expand the knowledge base and fill in the identified knowledge base. The findings are summarized in the table below:

Table 3: State-of-the-art findings summary

Topic	Finding
Digitalization and automation of ETO value chains	The impact of digital technologies implementation is not supported by empirical evidence in literature. The research presented in paper I is an attempt at bringing empirical evidence towards sustaining the hypothesis that specially developed digital solutions have the potential of addressing the traditional trade-off between flexibility and automation.
Sensor based programming of welding robots	Sensors based welding provides the necessary input for the welding robot to adapt its position relative to the welding seam. However, it is not clear how sensors-based methods can be used in a cost-effective manner without having prior information about the locations of the weldments around the item.
CAD based programming of welding robots	Researched extensively and many approaches exist on how CAD based programming of welding robots can be performed. However, a knowledge gap is identified on how ISO 2553 compliant annotations can be used to program welding robots. Although a program can be generated, offsets between the CAD model and the real product are not compensated for.
Hybrid programming of welding robots	Employs the benefits of both CAD based programming methods and sensor-based programming methods. However, based on the findings regarding CAD based programming the implications of using ISO 2553 compliant annotations are not yet clear
Product-process-resource-models	PPR perspective offers a comprehensive view on the value chain and the information which flows across it about the product which is intended to be

	manufactured and the capabilities of the manufacturing system. It is discovered in literature that PPR has been used for assembly applications, but no research was done before on how the PPR perspective can benefit robotic welding operations.

4.2. STATE OF PRACTICE AT CASE-COMPANY

This section describes the state-of-practice for order handling at Sjørring Maskinfabrik. The reader will be provided with understanding on how the information is processed along the value chain to obtain a welding-robot program ready to be deployed in production by using the PPR perspective. The data collection was made by the researcher through observations with full access to the company's value chain and in collaboration with the company's project manager, engineering manager, production manager, head of supply chain and CEO.

The case company has 199 employees out of which 152 are blue-collar employees who conduct shop-floor production operations through tasks like welding, cutting, and bending. Consistent with the current situation in high-cost environments, the company must rely more and more on automation. The company is structured in ten distinct departments: management, sales and marketing, customer service, finance, supply chain, engineering, quality assurance, production preparation, production, and IT. The departments which are responsible for the information flow are required to program welding robots are sales and marketing, engineering, production preparation and production.

4.2.1. VALUE CHAIN MAPPING – INFORMATION FLOW

Flexibility and fast reaction to customer and market demands are paramount on the value chain of an engineering-to-order small-medium enterprise. The order penetration point is right at the level of the sales department, most of the order being unique and every new customer order is a new project in itself that requires engineering resources. A value chain mapping was conducted in collaboration with company's project manager, engineering manager, production manager, head of supply chain and CEO. The value chain mapping has in focus the information flow leading up to welding-robot programming and has encompasses in its scope the sales operations, the product engineering operations, and the production engineering operations.

The value chain mapping is represented in Figure 15, where the information flow can be followed across several operations. The order enters the value chain through the sales operation where the product's requirements are set together with a sales manager. Once the basic product requirements are understood, a project is initiated, and engineering resources are allocated. Depending on the uniqueness of the customer's requirements, a completely new design is engineered or an existing one is adjusted to match the customer's requirements. The new, or the adjusted design is presented to the customer by the sales manager. If the design does not satisfy the customer, it is adjusted further by the product engineers. Once the design is approved by the customer, the design is documented and drafted to be sent to the production preparation department. At the level of the sales and product engineering departments, the engineering to order nature of the enterprise becomes apparent.

The robotics engineers located at the level of the production engineering and planning department use an offline programming system to process the product information received from the Product Engineering departments and program the welding-robots. The product information is organised as CAD models and printed drawings which are exchanged across departments on USB-sticks, via e-mail or simply handed over. Once the CAD model is imported inside the Panasonic DTPS OLP system, any information contained in that model as ISO 2553 compliant annotations concerning the welding process are lost. Therefore, the robotics engineers rely on printed technical drafts to locate the weldments and program the welding-robots accordingly. The process parameters required to program the welding robot are set using the worker's experience and tacit knowledge. Once the programming process is completed, the robot program is set to the production floor where is validated and robot welding can start.

To validate the robot program, the item to be welded is loaded into a specially designed fixture which can be easily adapted to the item’s shape. Adaptable fixtures are one of the main competences of the case-company and they are not in the focus of this research project.

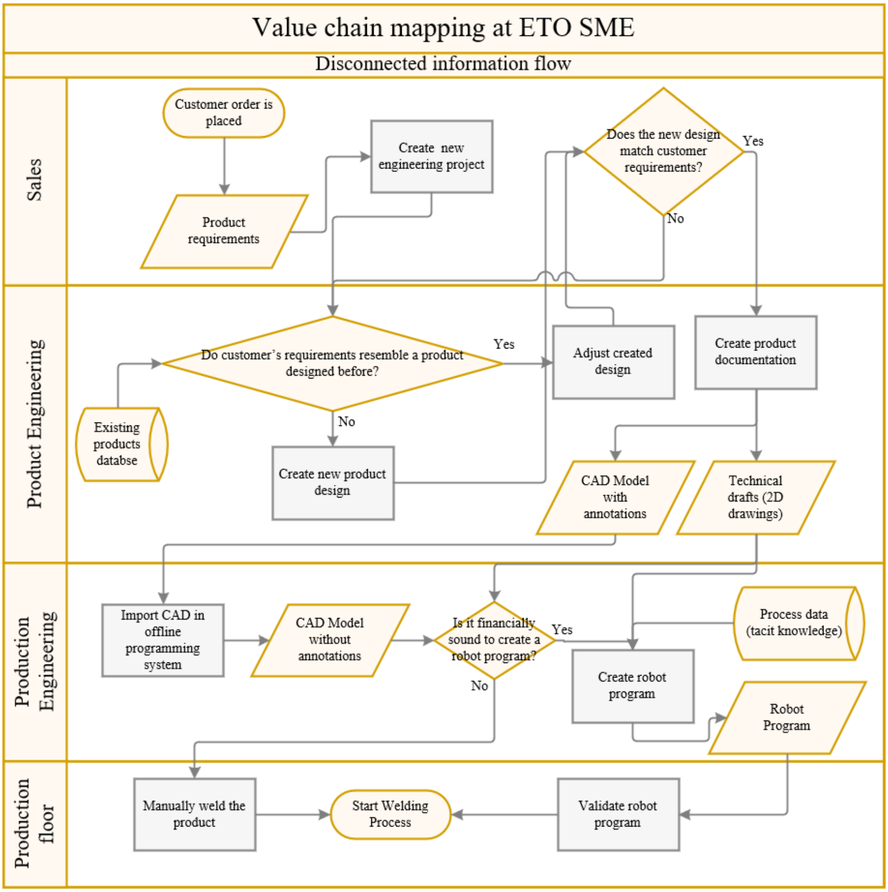


Figure 15: Cross-functional flow chart of the value chain of the case enterprise's value chain

Depending on the complexity of the product ordered and the quantity of the order, the robotics engineers decide if it is cost-effective to program and use welding-robots to produce the ordered item. Therefore, as observed in Figure 15, if the programming effort cannot be justified in terms of order quantity, the item is produced using manual welding. At the studied case company, if the ordered quantity is less than five pieces, the item is manually welded without further deliberation due to the time required to program the welding robots which significantly increase the lead time, as suggested in Figure 16. The programming of welding robots can add up to one week to the order's lead time. It is to be mentioned that although the welding time is limited by the travel speed of the welding torch which is a process parameter with influence over the quality of the weldment, the robotic cell has a shorter cycle time than a manual welding cell as it can function without breaks, unlike a human welder. As seen in Figure 16 programming of welding robots also takes a considerable part of the lead time. Being aware of this problem, robotics engineers often choose to send the item for manual welding instead, which compromises the utilization rate of the welding robots.

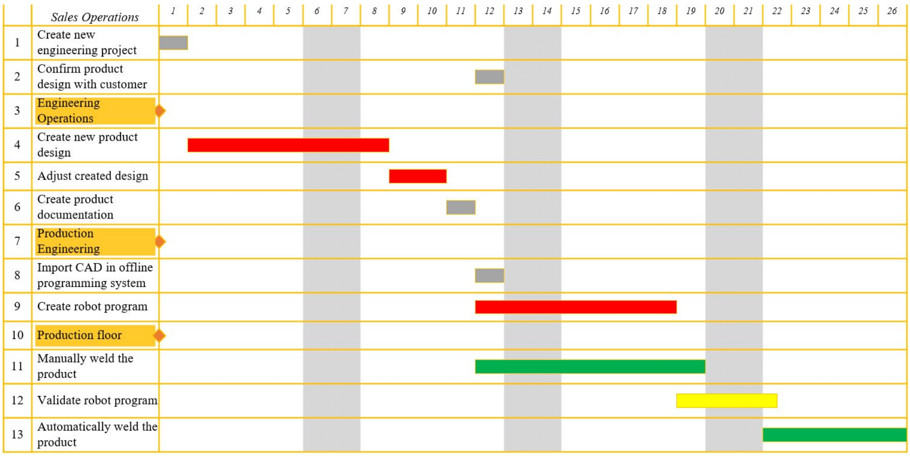


Figure 16: Gantt chart presenting the amount of time (in days) taken for various value adding operations. It can be observed that the tasks marked with red significantly increase the lead time of the product. By manually welding the product, the lead time is significantly shorter. The adjacent operations around production such as materials transportation and raw material preparation before welding are not in the scope of this research.

The Gantt chart in Figure 16 provides a visualisation on the main bottlenecks across the value chain, namely the creation of a new product design based on the customer's requirements and the programming of welding robots. Although, the programming of welding robots can be replaced by welding the product manually, the immediate results are low utilisation rate of the welding robots and increased reliance on manual labour.

4.2.2. WELDING-ROBOT-PROGRAMMING – PPR PERSPECTIVE

To understand the wide range of information required to successfully program a welding-robot, the PPR perspective (product-process-resource) is adopted using the template proposed by (Martínez-Olvera and Shunk 2006), and adapted as represented in in Figure 17. The order enters the value chain through the sales department and marketing department where the product’s requirements are set between a customer and a sales manager. The sales manager gathers information about the application which must be satisfied by the new product design which is demanded by the customer.

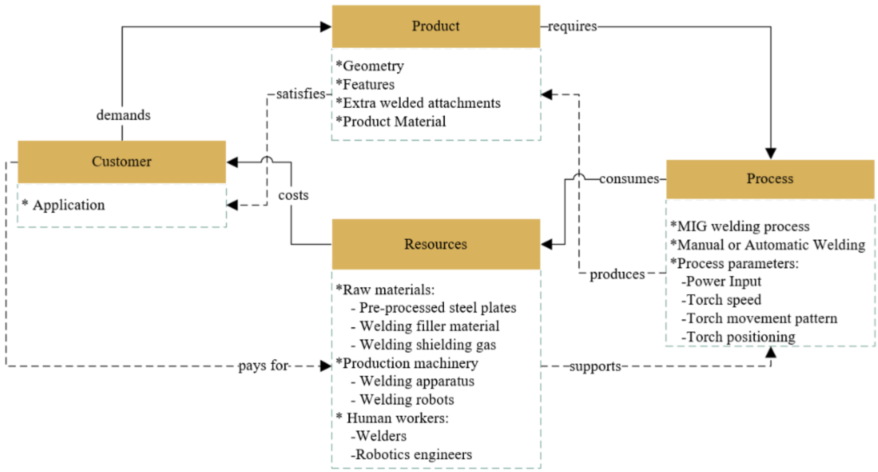


Figure 17: PPR (product-process-resource) perspective diagram over information concerning a welded product at Sjørring Maskinfabrik (Martínez-Olvera and Shunk 2006).

The product domain (P):

The case company has a product offering composed of both OEM (original equipment manufacturer) products and products sold under its own brand of about 25% at the moment of writing this thesis. For the OEM product offering, the customer is heavily involved in the design stage of the product, while the own brand products have a well-defined product family the customer can choose from. However, the variety between products is high and engineering is required for every new variant which was never produced before. Given the design parameters of each product family, it is estimated that up to one million variants can exist while the company sells about 12000 items yearly. This makes robot programming a heavy obstacle in the path of end-to-end automation, as the programs need to be adapted or re-written every time a new product variant is demanded, while there is no certainty about the design of the next product which will be demanded by the customer.

Once the basic product requirements which will satisfy the customers are made clear at the level of sales operations, a project is initiated, and engineering resources are allocated. Depending on the uniqueness of the customer's requirements, a completely new design is engineered or an existing one is adjusted to match the customer's requirements involving back and forth exchange of information between the product design engineers and the customer through an iterative process which takes a significant part of the lead time. This observation confirms the finding made by Jünge et al. about ETO enterprises (Jünge et al. 2023) who also found wasteful operations in ETO manufacturing systems. The final design is presented to the customer by the sales manager and a price is agreed upon. If the design does not satisfy the customer, it is adjusted further by the product engineers. Once the final design is approved by the customer, the design is documented and drafted to be sent to the production preparation department.

The geometric design of the product is the most significant element of the engineering process, and a CAD system (SolidWorks from Dassault Systèmes) is used to create it and adjust it. The CAD system used by the case-company is compliant the standard ISO 2553:2019 and weldment features can be created directly on the 3D geometric model and can be annotated. The annotations contain design information such as filler material and weldment throat size. These annotations appear on the technical draft of the product: bill of materials, manufacturing bill of materials and 2D technical drawings. The material of the product is another important element relevant for the proper setup of the process required to produce the product as it directly affects welding process parameters. The design engineers can further intervene and create extra welded attachments depending on the application of the product.

The process domain (P):

At the level of the production preparation department, the robotics engineers receive the technical draft of the product and the properly annotated CAD model of the product. Depending on the complexity of the product ordered and the quantity of the order, the robotics engineers decide if the production process will be supported using manual welding or automatic welding. If the programming effort for welding-robots cannot be justified in terms of order quantity, the item is produced using manual welding. At the studied case company, if the ordered quantity is less than five pieces, the item is manually welded without further deliberation due to the time consumed to program the welding robots.

The robotics engineers use their skills and tacit knowledge gathered through training and extensive experience to select the proper process parameters which are used in the welding process: torch speed, power input, torch movement pattern and torch positioning. Other relevant parameters like the shielding gas used and filler wire material are kept the same across all the built products. The quality standard that needs to be achieved for the weldments at the case-company is ISO-5817 class D which requires visual inspection of the weldment by certified welders in order to classify it. Therefore, the company is relying on the proper training and the experience of the welders and the robotics engineers to set up the right process parameters which will yield weldments suitable for the required standard.

The resource domain (R):

The resource domain encompasses the wide range of elements necessary to support the production process, in this case MIG welding. For both manual and automatic welding, the welding process consumes raw materials: filler wire, shielding gas, joining parts and power. The production machinery must be able to support the welding process with the properly selected parameters. In the case of manual welding, some of the process parameters are fully dependent on the worker's skill and experience, e.g. the torch velocity. In the case of automatic welding, the process parameters are programmed by the robotics engineers beforehand. Therefore, in the case of manual welding, the human welders are a resource consumed by the process in a continuous manner on the whole duration of the process. The automatic welding process however can be conducted unsupervised, and the robotics engineers act as a resource only while programming the robots. One of the core competences of the case-company is the design of adaptable fixtures for welding. These fixtures ensures that the work piece does not move under the influence of the heat input, ensuring the accuracy of the welding torch along the welding seam. The adaptable fixtures are not however in the focus of this research project.

In the case of robotic welding, the robotics engineers create a welding program using an offline programming system. The offline programming system (OLP) offers the necessary tools to set up the process parameters and check if the available resources (robots) can successfully support the welding process: it is checked if all the weldment seams are in the reachable workspace of the robot. The CAD model of the product, which is received from the product engineering department, has a vital role in the proper programming of collision free movement patterns for the welding torch mounted as end-effector on the welding robot. However, any overlaid annotations are lost upon import in the OLP as these annotations are not widely supported by the standard CAD file format ISO 10303-21 (e.g. STEP, standard for exchange of product data) or the OLP simply does not handle overlaid information on STEP files. Therefore, any details about the weldment must be re-digitalized by the robotics engineers inside the OLP system using information available on the 2D drawings of the technical drafts, thus repeating the task made by the product design engineers and consuming the robotics engineers' time. With the re-digitalized information, the robotics engineers can set up the process parameters for welding (torch velocity, torch motion pattern, energy input and torch positioning) and use their skills effectively.

4.2.3. STATE-OF-PRACTICE FINDINGS AND OBSERVATIONS

By using the observations presented in the previous sub section, the diagram in Figure 18 is put together and following summary is made:

1. The product engineers use CAD systems to facilitate the design process of the products demanded by customers. The product design phase is as lengthy process which covers a significant part of the product's lead time. Many times, an existing CAD model is adjusted to fit the requirements of the customers, thus a variation of an existing product is created.

2. The product engineers store all the product information inside CAD models, including information connected to the quality requirements of the weldments under the form of annotations as provisioned by ISO 2553:2019 standard, by using CAD software tool compliant with the standard.
3. The weldment annotations are lost when the CAD model is imported inside the offline programming system. This requires the robotics engineer to rely on the technical draft and repeat the digitalization process of the weldment information, specifically the locations of the weldments.
4. The company relies on the tacit knowledge and experience of the welders and robotics engineers to set up the right process parameters to obtain a weldment that satisfies the customer's demands.

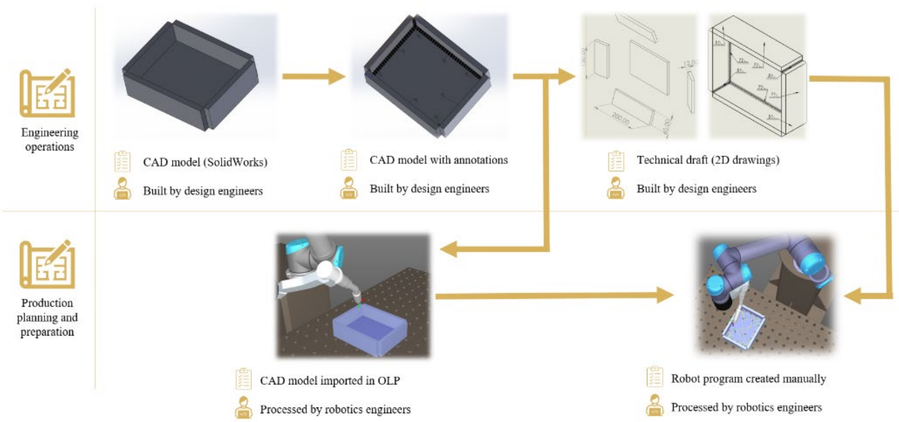


Figure 18: Programming of welding robots- state of practice on the ETO manufacturing system at Sjørring Maskinfabrik. The OLP illustrations in the figure were created using RoboDK, however Sjørring is using Panasonic DTPS supplied by Valk Welding

The main issue found at the ETO case-company is the utilisation rate of the robots which is not at capacity because in most of the cases it is preferable to have the shortest possible lead time by using manual welding instead of adding the necessary time to program the welding robots which may compromise the delivery dependability of the order. Even though the programming of welding robots is conducted using an OLP and it is not conducted online, the programming is still long enough to create a bottle neck at the level of the production preparation department. During the programming process of the welding robots, the robotics engineers use both the CAD model of the product without any welding annotations, and the technical documentation of the product to generate a welding program. This implies that the digitalisation process of the quality requirements for the weldment is repeated in two places:

1. First, at the level of the engineering operations, when the product is designed in collaboration with the customer, and the weldment requirements are annotated on the CAD model.

2. Second, at the level of the production preparation operations, when the robotics engineers use both the CAD model which has lost the weldment annotations, and the technical draft to program the locations of the weldments seams and the process parameters inside the offline programming tool to obtain a welding robot program.

Following the state of practice survey at the case-company, it is concluded that the case-company will benefit from a technical solution which allows fast adjustment of product designs without the need for an iterative process, ideally where the customer can have more control over the product's design but without the assistance of the engineers. Although the company is using CAD software and OLP software, the data exchange between these two environments is made manually and is disconnected. By integrating the two software entities, it is expected that by integrating the two software entities, the information flow will become streamlined, and the lead time will be reduced.

CHAPTER 5. ARTEFACT DEVELOPMENT

Having established a knowledge base composed of findings within the field's literature and findings made on the state-of-practice at the case company, the relevance cycles can be conducted based on the requirements presented in Table 2. The result of each relevance cycle is a technical artefact which fulfils the set requirements. The development of the artefact is conducted iteratively, during the design cycle and the novel theory and methodology which are tested through experiments involving the resulted artefact are documented in the papers attached to this thesis.

As mentioned by Paul Gray in "Design Research in Information Systems" (Hevner and Chatterjee 2010a), the application of IT artifacts is in the focus of DSR, and it involves solving problems by using agile processes, creativity, and teamwork. To conduct the development, the researcher has used access to state-of-the-art robot-welding laboratories made available by Aalborg University (AAU), the Norwegian University of Science and Technology (NTNU), and FORCE Technology. Access to a metal fabrication production line and support with test objects was provided by Sjørring A/S, the case company. Know-how and software licenses were provided by SolidWorks, DriveWorks, RoboDK, and Valk Welding. Funding for the project was provided by the partners involved in the MADE W.S. 2.02-part project.

The developed artefact has in its scope the sales operations, the engineering operations (product design), the production preparation operations (welding-robot programming) and the production operations (welding with welding-robots) at metal fabrication companies. A visualisation of the artefact's scope can be observed in Figure 19 (Sarivan et al. 2023b). The conceptual aspects of the artefact were documented in the attached papers and in this chapter a purely technical description of the artefact will be provided, and the reader will be informed on what steps must be followed to replicate the results presented in the paper. As stated by (Hevner and Chatterjee 2010b), using DSR is not an attempt at developing concrete IT applications. The artefact resulted from DSR is meant to help the development of concrete IT applications or products and it serves as proof of concept, which increases the practicality of ideas, and their intrinsic value is that of advancing knowledge in a certain field. In the case of this research, the main idea is that welding-robots can be programmed automatically based on information automatically extracted from product models and that digital technologies have a positive impact on ETO value chains by balancing the trade-off between flexibility and automation. For example, in the case of the artefact developed and showed in Figure 19, the CAD system of choice is SolidWorks, however, the CAD system can in fact be any other ISO 2553 compliant

CAD system. However, the meta-artifact built with SolidWorks, successfully proves the design ideas as correct.

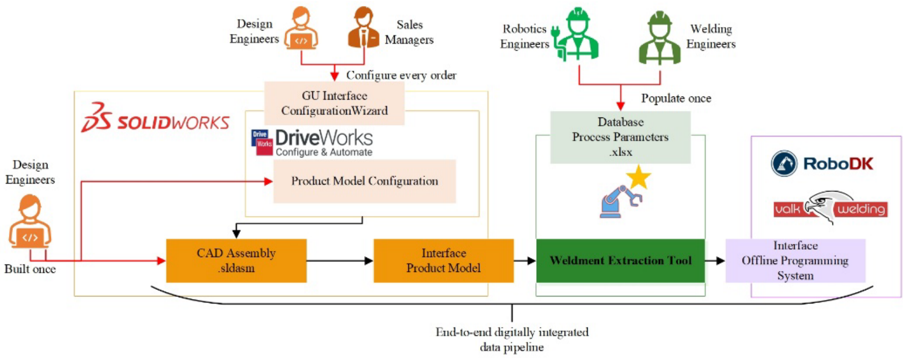


Figure 19: Overall scope and conceptual technical architecture of the developed artefact (Sarivan et al. 2023b)

(Hevner and Chatterjee 2010b) distinguishes between two types of knowledge entailed by resulting DSR IT meta-artefacts: *Design Product* and *Design Process* knowledge. The design product knowledge refers to the idea, the concept, the functionality, the behaviour, the architecture, the structure and possible instantiation of the meta-artefact. In the case of this project, the design product knowledge is encapsulated in the attached papers as presented in Table 4.

Table 4: Design product knowledge

Paper	**Topic**	**Product design knowledge**
I, (Bejlegaard et al. 2021)	Digital technologies can reduce the trade-off between automation and flexibility	Idea and concept
II, (Sarivan et al. 2022)	Data can be extracted from CAD models which can be used to program welding robots	Functionality and behaviour
III, (Sarivan et al. 2023a)		
IV, (Sarivan et al. 2023b)	PPR models encapsulate tacit knowledge necessary to set up the robotic welding process	Architecture, structure, and possible instantiation

The design process knowledge represents the physical processes necessary to be followed to realize the artefact (Hevner and Chatterjee 2010b). This chapter is focused primarily on the design process knowledge entailed by the proposed artefact for digital integration for automatic programming of welding-robots. (Hevner and Chatterjee 2010b) describe design process science as a set of instructions which take the following forms:

To achieve A, do (act_1, act_2, …, act_3)
If you want A and you believe that you are in a situation B,
then:
- you should do X
-it is rational for you to do X
-it is profitable for you to do X.

The sections of this chapter will also be organized as a set of instructions which practitioners can follow in order to design and develop similar artefacts like the one presented in this thesis. The instructions will be provided for the reader under each headline of sections 5.1, 5.2, and 5.3. As it will also be noticed, these three sections reflect the PPR perspective which was thoroughly described in paper IV attached to this thesis. Together with the instruction specific to each section, the PPR element afferent to that section will also be mentioned (Sarivan et al. 2023b).

The product showed in Figure 3 and Figure 4 will be used as example in the meta-artefact's process knowledge description.

5.1. AUTOMATIC CONFIGURATION OF PRODUCT MODELS AND WELDMENT ANNOTATIONS

To achieve <u>automatic configuration of product models</u> for automatic programming of welding robots, you must create mathematical definitions of your product, employ standardization across products and use ISO 2553.

The focus of this section is on establishing the product dimension of the PPR perspective.

5.1.1. CAD MODEL CREATION

To make possible the automatic configuration of product models for automatic programming of welding robots, the first step is to create a CAD model of the product intended for welding in a rigorous manner, especially when it comes to component naming. In this chapter, the product presented in Figure 4 will be used as example for automatic programming of welding robots based on product models. The product's CAD model is composed of six distinct components as shown in Figure 20. When manufactured, these components are metal sheets of various thickness which are bent to meet the design characteristics of the product. After being bent, the components are welded together using a robot-welder which will be programmed automatically.

As explained in section 1.4 of this thesis, a weldment is realized between a base component and a joining component. This is reflected in the naming of the product's components as shown in Figure 20.

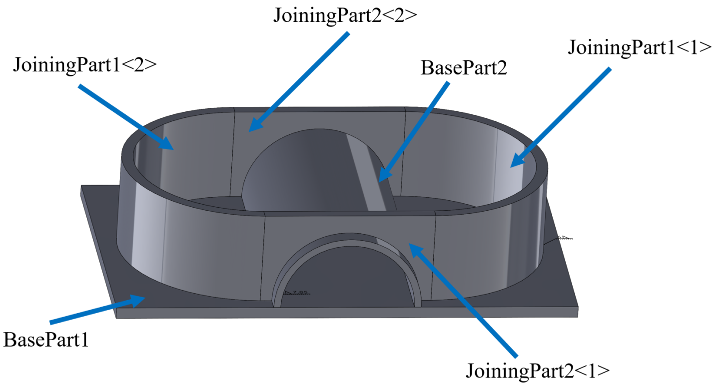


Figure 20: The product used as example in this chapter is composed of six distinct components which are welded together.

5.1.2. CREATION OF WELDMENT ANNOTATIONS

To create the product model entity as showed in Figure 19, a CAD model and the overlaid engineering-based knowledge for welding under the form of ISO 2553 compliant annotations must be built first. The "Weld Bead" tool available in the SolidWorks CAD system can be used. When deployed, the "Weld Bead" tool prompts the design engineer to select a "base face", marked with blue, and the "joining face", marked with pink in Figure 21. The "base face" must be selected to be as part of a "base component", as showed in Figure 20, and a "joining face" must be selected as part of a "joining component" The "Weld Bead" tool can be deployed from the "Weldments" toolbar in SolidWorks (Dassault Systemes 2023a). The expected thickness of the weldment is added in the dimension box as showed in Figure 21 and marked with colour orange. Further information can be added about the weldment by using the menus available in the "Weld Bead" panel as shown on the left-hand side of Figure 21. The resulted welding annotations are showed in Figure 4.

With the creation of weldment annotations complete, it is now possible to scale up or scale down the CAD model and the weldment annotations will remain affixed to the afferent weldment seam. However, depending on the extent of the change, intervention is required over the annotations e.g., in case the thickness of the joining plates is changed. Therefore, a product model is desired to be created which will allow the automatic adjustment of these design parameters based on the thickness of the plates.

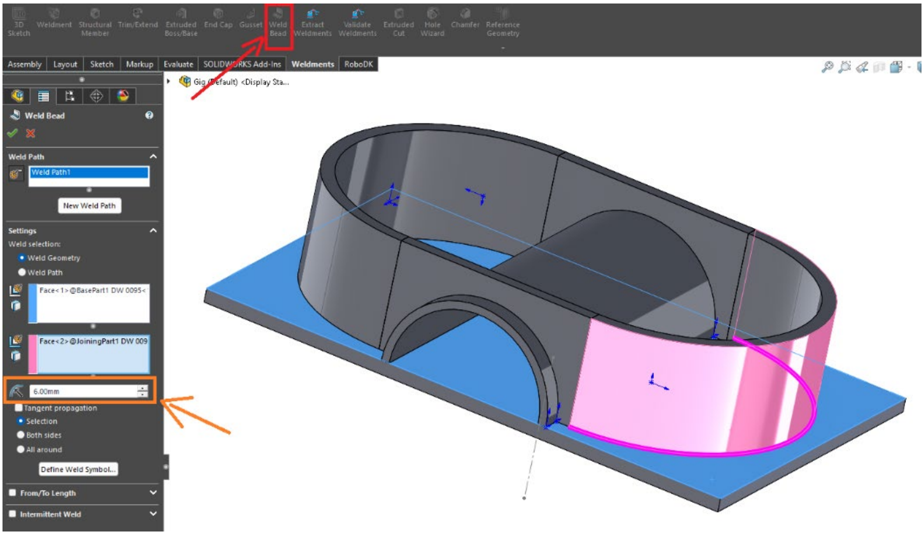


Figure 21: The "Weld Bead" tool is deployed. The "base" face was selected by the design engineer and marked with colour blue. The joining "face" was selected by the design engineer and marked with colour pink.

5.1.3. CREATION OF RULE BASED PRODUCT MODEL

To prevent manual intervention from the design engineer over the CAD model every time a new product variant is necessary, the CAD model can be parameterized. Parametrization allows accessible product configuration even by untrained personnel. To achieve this, the DriveWorks add-on for SolidWorks Solo is used (DriveWorks). The DriveWorks Solo add-on makes it possible for mathematical ruled to be built which define the product model and allows for product variants to be created by using configuration wizards.

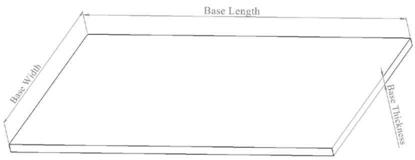
Traditionally, the engineers must intervene over each component of the CAD model to adjust the geometric design parameters of the product. For the test product in Figure 20, there is a total of thirty-two parameters which must be adjusted in order to match the customer's requirements. The design parameters can be observed in Table 5. By using the tools made available through DriveWorks, mathematical expressions can be defined for all design parameters to be adjusted automatically. The design parameters have therefore been reduced by a factor of eight, to only four configuration parameters. A configuration wizard which provides an interface for the new configuration parameters has been implemented as shown in Figure 22. Based on the values which are inserted in the configuration wizard, the parametrization formulas are showed in Table 6.

Table 5: Design table for the experimental product in Figure 20

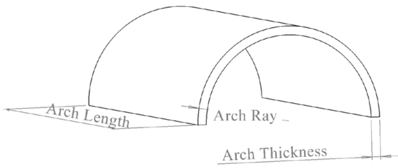
BasePart1: - Base Length - Base Width - Base Thickness	**BasePart2:** - Arch Ray - Arch Thickness - Arch Length	**JoiningPart1<1>:** - End Ray - End Height - End Thickness
JoiningPart1<1>: - End Ray - End Height - End Thickness	**JoiningPart2<1>:** - Segment Length - Segment Arch Ray - Segment Height - Segment Thickness	**JoiningPart2<2>:** - Segment Length - Segment Arch Ray - Segment Height - Segment Thickness

Weldments:			
Weld1: -Thickness -Length	**Weld2:** -Thickness	**Weld3:** -Thickness -Length	**Weld4:** -Thickness
Weld5: -Thickness -Length	**Weld6:** -Thickness	**Weld7:** -Thickness -Length	**Weld8:** -Thickness

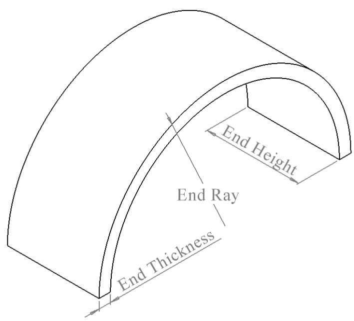
Base Part 1



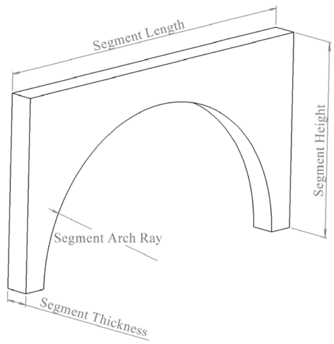
Base Part 2



Joining Part 1 <1>&<2>



Joining Part 2 <1>&<2>



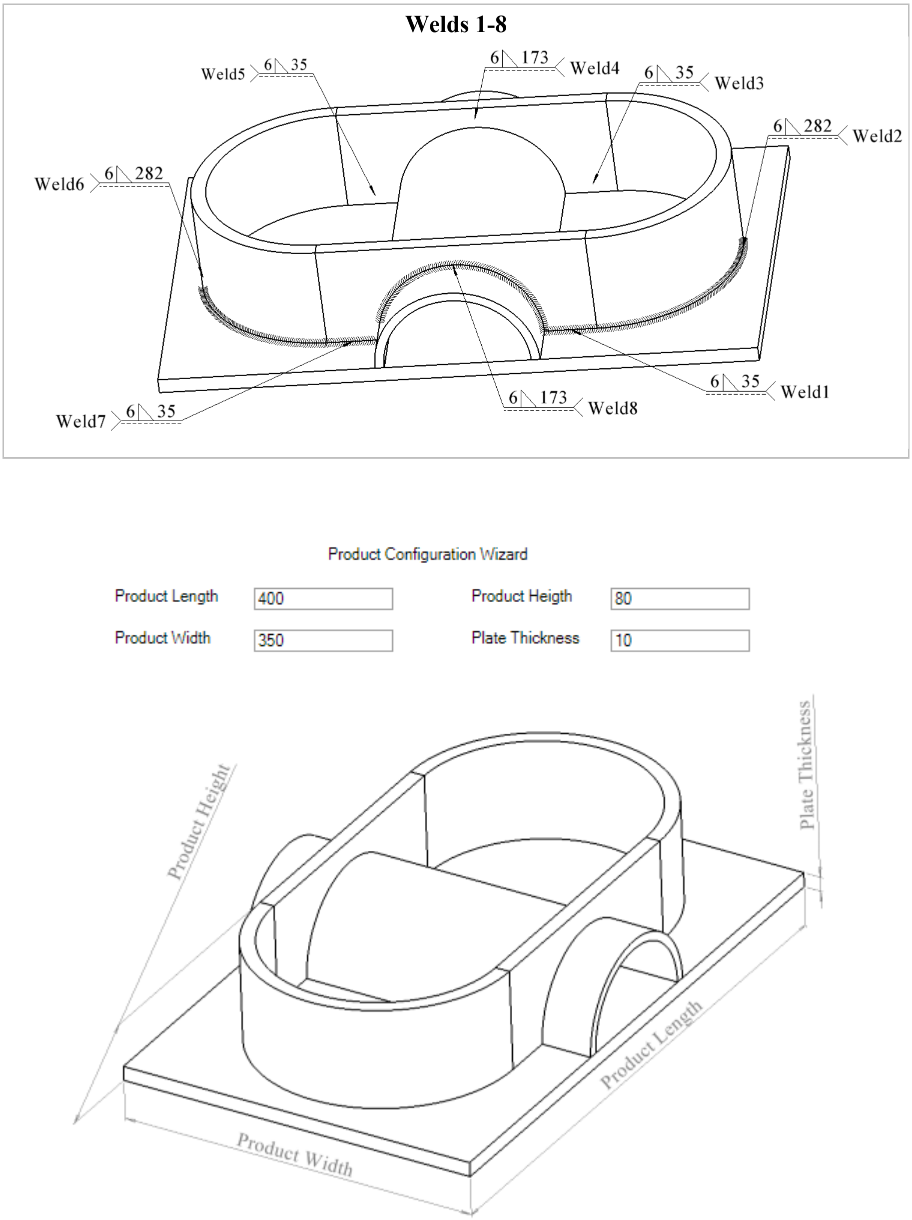


Figure 22: Product model configurator for the test product containing less design parameters than the original CAD model with a factor of eight.

Table 6: Parametrization table for the test product in Figure 20.

Component	Dimension	Formula
Base Part 1	Base Length	= “Product Length”
	Base Width	= “Product Width”
	Base Thickness	= “Plate Thickness”
Base Part 2	Arch Ray	= “Product Height” - 15 - “Plate Thickness”
	Arch Thickness	= “Plate Thickness” - 4
	Arch Length	= “Product Width”
Joining Part 1 <1>&<2>	End Ray	= (“Product Length” – 40) / 4
	End Height	= “Product Height” – “Plate Thickness”
	Arch Thickness	= “Plate Thickness”
Joining Part 2 <1>&<2>	Segment Length	= (“Product Length” - 40) / 2
	Segment Arch Ray	= “Product Height” - 15 – “Plate Thickness”
	Segment Height	= “Product Height – Plate Thickness”
	Segment Thickness	= “Plate Thickness”
Weld 1	Thickness	= Int (“Plate Thickness” * 2 / 3)
	Length	= (“Product Length” - 40) / 4 - (“Product Height” - 15 – “Plate Thickness”)
Weld 2	Thickness	= Int (“Plate Thickness” * 2 / 3)
Weld 3	Thickness	= Int (“Plate Thickness” * 2 / 3)
	Length	= (“Product Length” - 40) / 4 - (“Product Height” - 15 – “Plate Thickness”)
Weld 4	Thickness	= Int (“Plate Thickness” * 2 / 3)
Weld 5	Thickness	= Int (“Plate Thickness” * 2 / 3)
	Length	= (“Product Length” - 40) / 4 - (“Product Height” - 15 – “Plate Thickness”)
Weld 6	Thickness	= Int (“Plate Thickness” * 2 / 3)
Weld 7	Thickness	= Int (“Plate Thickness” * 2 / 3)
	Length	= (“Product Length” - 40) / 4 - (“Product Height” - 15 – “Plate Thickness”)
Weld 8	Thickness	= Int (“Plate Thickness” * 2 / 3)

With the configuration wizard represented in Figure 22 set up, it is possible to configure variations of the product represented in Figure 20. Three variations are showed in the figure below with the design parameters represented in Table 7.

Table 7: Design parameters of three variants of the test product in Figure 20.

	Product Length	Product Width	Product Height	Plate Thickness
Item 1	400	250	80	10
Item 2	500	350	100	12
Item 3	700	500	120	15

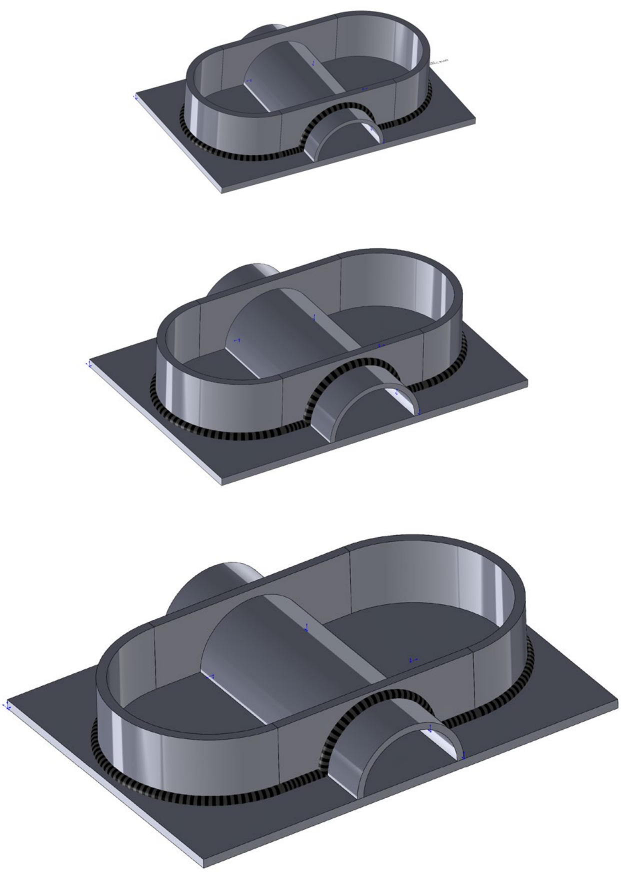


Figure 23: From top to bottom: Item 1, Item 2 and Item 3 defined in Table 7.

The product variations showed in Figure 23 have been automatically generated using the configuration wizard represented in Figure 22. Alongside the dimensions of the welded components, the ISO 2253 weldment annotations themselves have also been automatically adjusted to fit the dimensions of the product, including the thickness of the plates. As observed in Table 6, the weldment's thickness is set to be one third of the thickness of the plates. This setting and other parameter too which are expressed numerically in the table can be adjusted by the design engineers if desired so. Manually adjusting the parameters would be a case of dedicated flexibility, while the configuration wizard ensured dedicated automation. The cases of dedicated flexibility and dedicated automation are documented in paper I attached to this thesis (Bejlegaard et al. 2021). The parametrization of the product's design drastically reduces the time required to adjust it based on customer's requirements.

5.2. WELDMENT GEOMETRY EXTRACTION FROM ISO 2553 ANNOTATIONS

To achieve automatic trajectory generation for complex geometries, you must extract the weldment's geometry from the ISO 2553 annotations and then divide the weldments into prismatic, quasi-stationary components (Sarivan et al. 2023a).

The focus of this section is on establishing the Process dimension of the PPR perspective. Namely how to setup the welding process using data from the product.

To extract the weldment geometry directly from the ISO 2553 annotations, it is necessary to use SolidWorks' application programming interface (API). The API gives direct control over the CAD model, its feature tree (represented in Figure 24), and its overlaid information e.g., ISO 2553 weldment annotations. The API makes it possible for a stand-alone Microsoft Windows application to be built inside the Visual Studio integrated development environment (IDE) provided by Microsoft. The programming language used is C#.

To build the Windows application necessary for extracting the geometry of the weldments, the SolidWorks API documentation provided by Dassault Systèmes can be used (Dassault Systemes 2023b). In this section, an overview of the necessary principles and general steps which must be followed to achieve this application are given.

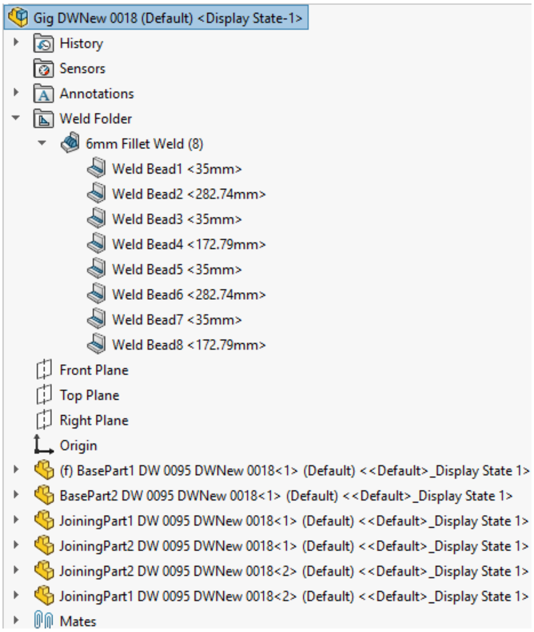


Figure 24: Feature tree for the CAD model of the object represented in Figure 20.

5.2.1. OBTAINING HANDLERS ON THE ANNOTATIONS

To extract the weldment's geometry information directly from the ISO 2553 annotations, handlers are required. A handler is the manner in which data can be accessed programmatically from inside the feature tree showed in Figure 24. The target of the handlers will be the "Weld Bead" features located inside the "Weld Folder". The SolidWorks API has available the method "*SelectByID*", which makes it possible to obtain the handler for the weldment. The ID in this case is "Weld Bead" followed by the order number of the weldment. This means that the weld bead feature cannot be named in any other way when the annotations are created as explained in subsection 5.1.2.

While creating weldment annotations as showed in subsection 5.1.2, it is possible that the numbers in the weldment's IDs are not consecutive, e.g. "Weld Bead5" followed by "Weld Bead 79". This will not be a problem for the software as long as the difference between the IDs is not greater than 1000. With the weldment handlers obtained, it is then possible to extract the geometry of the weldment.

5.2.2. OBTAINING WELDMENT TESSELATION POINTS

To obtain the geometry of the weldment, the tessellation feature of CAD systems is exploited. Tessellation points represent the elementary and discrete building block of the CAD model, every line segment within the CAD model being composed of a finite number of tessellation points. The number of tessellation points usually depends on the performance of the computer being used and the performance of the CAD system. A line segment which is relevant in the hereby case is the edge between the base and joining components on which the weld feature is attached to. The edge can be accessed by using the "Weld Bead" handlers obtained in the previous step and the available "*GetEntitiesWeldPath*" method. The edges on which Weld1 and Weld2 are attached to are highlighted in Figure 25. An overview on Weld1 and Weld2 is showed in the product's design Table 5.

Having obtained handlers for the edges on which the welds are attached to, it is now possible to access the tessellation points for each edge by using the "GetTessPts" method. One of the arguments this method takes is the minimum distance allowed between the tessellation points and returns the coordinates of each tessellation point relative to the origin of the CAD model. In the case of this project the minimum distance between the tessellation points is set to be five millimeters. It is assumed this resolution is sufficient to meet most of the applications addressed by the software. This resolution is only relevant for curved edges, where multiple points are necessary to define them, and the SolidWorks API will approximate to it as much as possible. In the case of straight weldments like the weldment on the left-hand side of Figure 25, only two points are necessary to define the weld path. The SolidWorks API can be used to determine the coordinates of these two points, which are returned in an array as showed on the left-hand side of Figure 26. Each set of three elements defines the x, y, z coordinates of one tessellation point. For example, elements with indexes 0, 1, and 2 define the coordinates of the first tessellation point for the straight edge in Figure 25, while elements with indexes 3, 4 and 5 define the coordinates of the last tessellation point for the straight edge. The same applies for every tessellation point defining the curved edge as observed in Figure 26 on the right-hand side. The curved is therefore defined by 35 (105 array elements divided by three coordinates for each point) points with approximately eight millimeters in between.

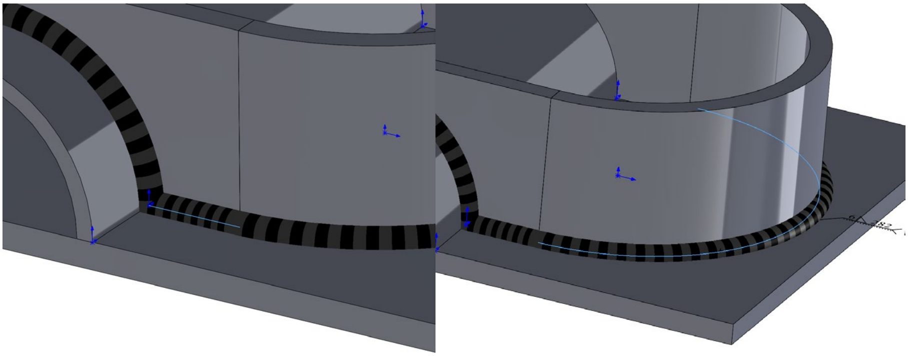


Figure 25: The edges on which the weld annotations are attached to are highlighted with blue. These edges are composed of a finite number of tessellation points.

weldmentEdgeTesselationPoints	{double[6]}
[0]	0.25500000000000067
[1]	-0.21499999999999922
[2]	0.010000000000000909
[3]	0.29000000000000065
[4]	-0.21499999999999908
[5]	0.010000000000001027

weldmentEdgeTEsselationPoints	{double[105]}
[0]	0.29000000000000076
[1]	-0.21499999999999886
[2]	0.010000000000001003
[3]	0.298473498553042
[4]	-0.21460022222222108
[5]	0.010000000000001032
[6]	0.30687171896338239
[7]	-0.21340444049492344
[8]	0.01000000000000106
[9]	0.31512005185562342
[10]	-0.21142327808392031
[11]	0.010000000000001088
[12]	0.32314521944767549
[13]	-0.20867433553823583
[14]	0.010000000000001116
[15]	0.33087592654695536
[16]	-0.20518203432769566
[17]	0.010000000000001142
[18]	0.3382434939333564

Figure 26: Set of tessellation points for weldment edges showed in Figure 25. Screenshots taken from the Visual Studio's debugger session while extracting the weldment geometries.

5.2.3. OBTAINING BASE AND JOINING SURFACES NORMALS

The coordinates of each point which composes a weldment's edge have been determined using SolidWorks' API. However, the issue remains when trying to establish which direction the weldment is facing towards. To establish the direction in which the weldment is facing towards, the surface normal of the joining and base surface can be used.

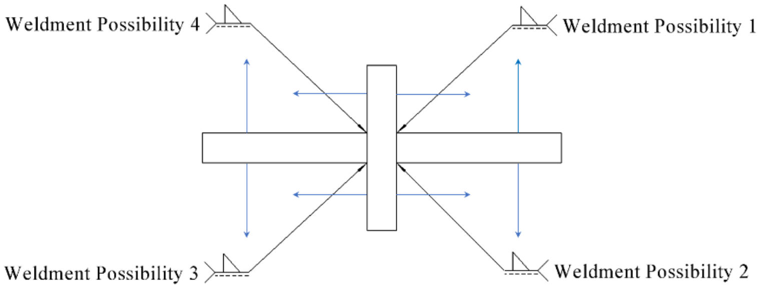


Figure 27: For some joints, there are multiple possibilities for where a weldment can be located. Therefore, it is not trivial to determine the orientation of the weldment or towards which direction the weldment is facing. The surface normal of each surface (indicated with blue arrows) can be used to determine which direction the weldment is facing.

The SolidWorks API makes it possible to determine the surface normal at a given location. This is an important feature, especially for curved weldments where the surface normal points towards different directions along it like the weldment represented on the right-hand side of Figure 25. To achieve this, first handlers for the joining and base surfaces must be established. Handlers can be obtained by using the "GetEntitiesWeldFrom" method for the base surface and the "GetEntitiesWeldTo" for the joining surface. These methods are members of the weldment's handler obtained as described in subsection 5.2.1. Once the handlers are obtained, the "EvaluateAtPoint" method can be used, which takes as arguments the coordinate of the tessellation point for which the normal must be determined. For the weldment showed on the left-hand side of Figure 25, the values showed in Table 8.

Table 8: Example of table containing position coordinates for tessellation points of weldment edge represented on the left-hand side of Figure 25 together with surface normal vector coordinates for the base and joining surfaces.

Position			**Base Surface Normal (vector)**			**Joining Surface Normal (vector)**		
X	**Y**	**Z**	**X**	**Y**	**Z**	**X**	**Y**	**Z**
0.255	-0.215	0.01	0	0	1	0	-1	0
0.29	-0.215	0.01	0	0	1	0	-1	0

5.2.4. ELEMENTARY WELDING OPERATIONS

Elementary welding operations can help to program the trajectories of the welding torch (position and orientation) automatically (Sarivan et al. 2023a). In simple terms, an elementary welding operation is defined from a geometric point of view as the segment defined between two tessellation points with the afferent information connected to it, as described in paper II attached to this thesis. The Elementary Welding Operation concept is built upon the assumptions that a weldment is composed of multiple prismatic and quasi-stationary components (Sarivan et al. 2023a), with the afferent structure represented in the UML diagram in Figure 28.

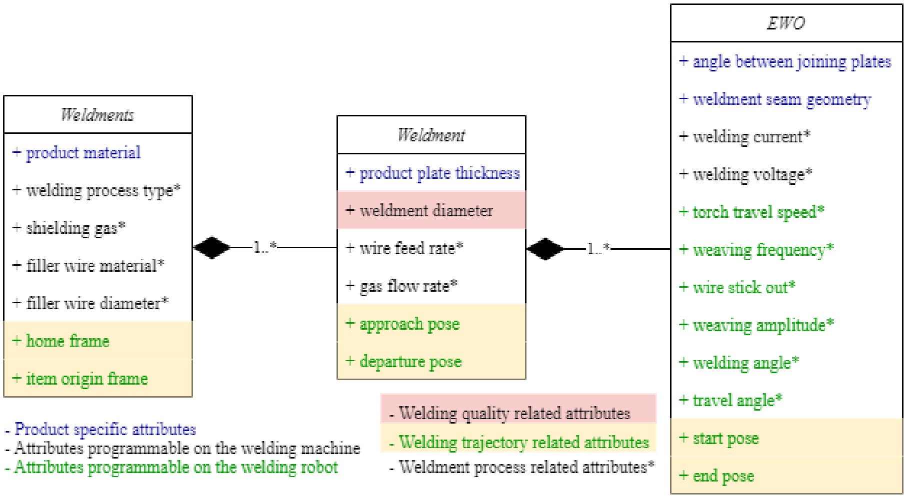


Figure 28: UML representation of the Elementary Welding Operations concept, as presented in paper III attached to this thesis (Sarivan et al. 2023a)

As described in paper III, once the position coordinates of the tessellation points and their afferent normal vectors for the joining and base surface have been determined, elementary welding operations can be built and the trajectory for the welding torch can be programmed using the "*start pose*" and "*end pose*" elements seen in Figure 28.

In the next subsection, it is intended to clarify how exactly the rest of the parameters are set up e.g., torch travel speed, weaving frequency, wire stick out, weaving amplitude, welding angle, travel angle, welding current and welding voltage. As described by (Lauridsen 1991), these are motion and arc parameters as also described in Figure 7. The architecture presented in Figure 28 is inspired from the work done by Lauridsen in 1991 in their attempt to automatize the programming of welding robots, which back then was significantly limited due to the computation and storage power at the time. The relevant parameters as described by (Lauridsen 1991) are also provided in Figure 8.

5.2.5. DIGITALIZATION OF TACIT KNOWLEDGE

Some of the parameters needed to program a welding robot are highly dependent on the application and the experience of the welder. Although welding procedures are put in place which are used to give welders directions on how to properly set up a welding process with the right parameters, the parameters are subject to change as the welders gain experience with the objects, they weld (Hughes 2009). Therefore, to achieve automatic programming of welding robots based on CAD models, one of the most important steps is the digitalization of the tacit knowledge held by the welders. In this project, the collaboration with the case company was instrumental in fulfilling this step. However, some of the offline programming systems, do have this knowledge integrated and readily available in their databases based on the weld throat size e.g., DTPS by Panasonic, supplied by Valk Welding (ValkWelding 2011).

Table 9: Table contains the digitalized motion and arc parameters which were determined via interviews with the experienced welders at the case-company.

	Item 1	**Item 2**	**Item 3**
Weld throat size (A-mål)	6mm	8mm	10mm
Welding current (I)	312 A	285 A	313 A
Welding voltage (V)	27.5 V	29.2 V	28.5 V
Torch travel speed (v)	0.0064 m/s	0.006 m/s	0.0048 m/s
Weaving frequency (f)	2.5 Hz	2.5 Hz	2.5 Hz
Wire stick-out (S)	0.018 m	0.018 m	0.018 m
Weaving amplitude (A)	0.028 m	0.03 m	0.03 m
Welding angle (α)	45°	45°	45°
Travel angle (β)	5°	5°	5°
Multi-pass (n)	0	3	3
Horizontal multi-pass offset (ΔX)	0	0.007 m	0.007 m
Vertical multi-pass offset (ΔZ)	0	0.007 m	0.007 m

As showed in Figure 19, the tacit knowledge of the workers is digitalized under the form of a Microsoft Excel table which is used to look-up the arc and motion parameters based on the weld's throat size. The weld's throat size, as showed in Table 6, is set as two thirds of the thickness of the thickest welded plate. The parameters showed in Table 9 can differ from manufacturer to manufacturer and from product to product.

5.2.6. OUTPUT FROM AUTOMATIC CONFIGURATION OF PRODUCT MODELS

The previous subsections of section 5.2 have showed to the reader how automatic extraction of weldment geometry is possible based on automatically generated product model based on configurations set in configuration wizards. This current subsection is meant to explain to the reader the expected output of the previously described system.

The output of the extraction system from ISO 2553 compliant weldment annotations is structured under the form of an XML file. The XML file has the structure showed in Table 10 below.

Table 10: XML output of the information extracted from ISO2553 weldment annotations.

```
<Weldments ProductName="Item1" ProductMaterial="SSAB 335MC" WeldingProcessType="MIG"
ShieldingGas="82Argon18CO2" FillerWire="G3SI1" FillerWireDiamater="1.2">
  <Weldment No="1" Id="1-2-3" ProductPlateSize = "10" WeldBeadSize="6" WeldBeadLength="352.74"
WireFeedRate="Auto" GasFlowRate="Auto">
      <EWO No="1" StartPose="Pose" EndPose="Pose" WeldingAngle="45" TravelAngle="5"
WeldingCurrent="312" WeldingVoltage="27.5" TorchVelocity="0.0064" WeavingFrequency="2.5"
Stickout="0.018" WeavingAmplitude="0.028" Multipass="0" MultiPassOffset="0" />
      . . .
      <EWO No="36" StartPose="Pose" EndPose="Pose" WeldingAngle="45" TravelAngle="5"
WeldingCurrent="312" WeldingVoltage="27.5" TorchVelocity="0.0064" WeavingFrequency="2.5"
Stickout="0.018" WeavingAmplitude="0.028" Multipass="0" MultiPassOffset="0" />
 </Weldment>
    . . .
  <Weldment No="4" Id="8" ProductPlateSize = "10" WeldBeadSize="6" WeldBeadLength="352.74"
WireFeedRate="Auto" GasFlowRate="Auto">
      <EWO No="1" StartPose="Pose" EndPose="Pose" WeldingAngle="45" TravelAngle="5"
WeldingCurrent="312" WeldingVoltage="27.5" TorchVelocity="0.0064" WeavingFrequency="2.5"
Stickout="0.018" WeavingAmplitude="0.028" Multipass="0" MultiPassOffset="0" />
      . . .
      <EWO No="26" StartPose="Pose" EndPose="Pose" WeldingAngle="45" TravelAngle="5"
WeldingCurrent="312" WeldingVoltage="27.5" TorchVelocity="0.0064" WeavingFrequency="2.5"
Stickout="0.018" WeavingAmplitude="0.028" Multipass="0" MultiPassOffset="0" />
 </Weldment>
</Weldments>
```

As observed in the XML file from Table 10, welds with numbers one, two and three from Figure 20 are structured together. This is because the weldment arc does not have to be stopped when transitioning between these weldments. This is programmatically made possible when the distance between the weldments is lower than 10 millimeters and the angle between them is lower than 35°. This is also reflected in the number of elementary welding operations which compose the weldment which is 36. Initially, there were 34 elementary welding operations afferent to 35 tessellation points of weldment 2. With the extra two weldments (weldment 1 and 3) which have 2 tessellation points each, where one of the tessellation points coincides with the start and end tessellation points of weldment 2.

Observed in Table 10 is that the filler wire feeding rate and the gas flow rate are set to "Auto". This is because modern welding machines can automatically set the flow rate of gas and feeding rate of wire based on the energy input set by the welder. In this case, the energy input is set through the voltage and current settings.

It can further be noticed in Table 10 that the pose for the welding torch is set just as "Pose". This is due to space limitations in the word document. An example is given below in Equation 1 on the structure of the "Pose" matrix. In paper I attached to this thesis it is thoroughly explained how the values in the "Pose" matrix are obtained for each elementary welding operation (Sarivan et al. 2023a). It is to be mentioned that the values in Equation 1 are only valid for the particular case taken as example based on the product showed in Figure 20.

$$ {}^{Origin}_{EWO\ 1}T = \begin{bmatrix} 0 & 1 & 0 & 0.255 \\ -1 & 0 & 0 & -0.215 \\ 0 & 0 & 1 & 0.01 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

Equation 1: Transformation from CAD origin to weldment 1 - EWO 1

With all the data about the weldments gathered in a single XML document, it is now possible to automatically program a welding robot, as it will be explained in the next section.

5.3. AUTOMATIC PROGRAMMING BASED ON PPR MODELS

To successfully program a welding robot automatically, import the weldment information extracted from the ISO 2553 annotations into an offline programming system. The offline programming system generates a collision free program for the welding robot.

The focus of this section is on the Resource dimension of the PPR perspective. The resource in this case is the welding robot.

With all the necessary information to program the welding robot extracted from the ISO 2553 annotations, it is possible to automatically generate a collision free welding robot program using an OLP. In this project, two OLP systems were used: DTPS by Panasonic (supplied by Valk Welding) and RoboDK. The DTPS software supports direct import of all the information included in the XML document presented in Table 10, with the condition that the information is converted into json format. A complete overview of the whole system as such can be seen in Figure 19. The DTPS software has built-in databases for setting up weaving and multi-pass weldments based on the throat size of the weldment. Finally, the available automatic robot programming (ARP) system from Valk Welding automatically generated collision free trajectories for the welding robot (ValkWelding 2011; Valk Welding 2023).

This section will focus on the necessary implementation to automatically program a welding robot by using the RoboDK OLP, which does not have a direct method to directly import the data in the XML document in, but it does have an API which can be used to create such method and have all the information available in the XML document sent to the robot in the proper data format.

5.3.1. CONFIGURATION OF WELDING TORCH POSE

The pose information found in the XML document defines the pose of the weldment only relative to the origin of the CAD model. To properly define the pose of the torch relative to that of the weldment, the travel angle, the welding angle and the stick-out are used too in matrix computations. The transformation from the level of the weldment to the right pose for the welding torch is given below where α is the welding angle, β is the travel angle and S is the wire stick-out as showed in Figure 7.

$$
{}^{EWO\,n}_{Torch}T = \begin{bmatrix} -cos(\alpha) & -sin(\alpha)*sin(\beta) & -cos(\beta)*sin(\alpha) & S*sin(\alpha)*cos(\beta) \\ 0 & cos(\beta) & -sin(\beta) & S*sin(\beta) \\ sin(\alpha) & -cos(\alpha)*sin(\beta) & -cos(\alpha)*cos(\beta) & S*cos(\alpha)*cos(\beta) \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

Equation 2: Transformation from the weldment level to the welding torch's level.

By multiplying together, the matrices from Equation 1 and Equation 2, the following result is obtained:

$$
{}^{Origin}_{Torch}T = {}^{Origin}_{EWO\,1}T * {}^{EWO\,1}_{Torch}T
$$

$$
{}^{Origin}_{Torch}T = \begin{bmatrix} 0 & 0.996194 & -0.087155 & 0.256568 \\ 0.707106 & 0.061628 & 0.704416 & -0.227679 \\ 0.707106 & -0.061628 & -0.704416 & 0.022679 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

Equation 3: Transformation from the origin of the product to the torch level for the first EWO of the first weldment of the test product.

To import the matrix inside Equation 3 into RoboDK, the "SetPose" method of the RoboDK API is used which takes the matrix as argument. The complete result of importing the weldment geometry from ISO 2553 annotations inside the RoboDK OLP can be observed in Figure 29.

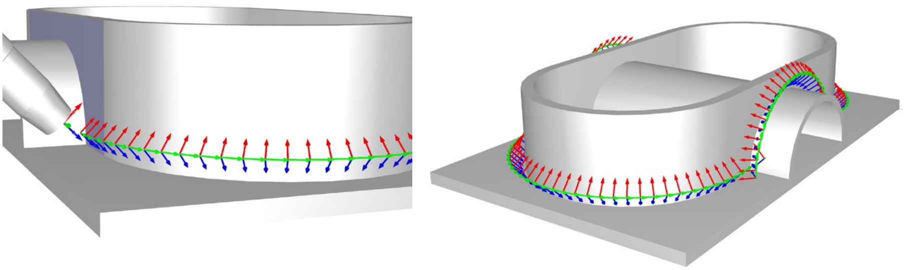


Figure 29: Result of importing weldment geometry inside the RoboDK OLP for weldments one, two and three on the left-hand of the figure. The pose of the torch in the first EWO is also visible. On the right-hand side of the figure, the complete result of the geometry import.

5.3.2. ARC-PARAMETERS IMPORT

Having successfully imported the geometry of the weldments inside the RoboDK OLP, it is possible to programmatically set up the arc parameters of the torch and some of the motion parameters like torch velocity. This is made possible by importing the parameters inside RoboDK when a torch target is created. The torch target can be identified in Figure 29 as the frames with red arrow afferent to the X axis, the green arrow afferent to the Y axis and the blue arrow afferent to the Z axis. The motion and arc parameters are passed to the constructor of the targets as arguments.

Figure 30: Table in RoboDK containing the target frames for the welding torch. The target frames contain the arc parameters (voltage and current) together with the velocity of the torch.

5.3.3. PROGRAMMING OF MULTI-PASS WELDMENTS

Multi-pass welding is necessary for welding items 2 and 3 as showed in Table 9. As explained in section 1.4, multi-pass welding is a solution for keeping the energy input under control for thicker weldments. To program the multi-pass welding, the root pass is taken as origin. An example of a root pass is showed in Figure 31, where the frames of the weldment path at the level of the weldment seam are also made visible for the reader. The root pass, however, is located at the level of the welding torch. To program the filler passes, the goal points of the root pass are offset with the afferent distance as showed in Table 9. In this project, the offset is selected to be seven millimeters both vertically and horizontally. The RoboDK API makes it possible to easily offset the trajectory by using the “transl” method which is available as member for the goal point’s handler. The “transl” method takes as arguments the frame relative to which the translation should be made, the distance of the translation and the axis along which the translation must be performed. A description of the “transl” method, is given in

Equation 4. As observed in Figure 31, the translation for the multi-pass offset must be made along the X axis and the Z axis of the frames placed along the weldment seam.

$$ {}^{Origin}_{Torch_{Pass1}}T = {}^{Origin}_{EWO\ 1}T * {}^{EWO\ 1}_{Offset\ Horizontal}T * {}^{Offset\ Horizontal}_{Torch_{Pass1}}T $$

$$ {}^{Offset\ Horizontal}_{Torch_{Pass1}}T = {}^{EWO\ 1}_{Torch}T $$

$$ {}^{Origin}_{Torch_{Pass2}}T = {}^{Origin}_{EWO\ 1}T * {}^{EWO\ 1}_{Offset\ Vertical}T * {}^{Offset\ Vertical}_{Torch_{Pass2}}T $$

$$ {}^{Offset\ Vetical}_{Torch_{Pass2}}T = {}^{EWO\ 1}_{Torch}T $$

$$ {}^{EWO\ 1}_{Offset\ Horizontal}T = \begin{bmatrix} 1 & 0 & 0 & 0.007 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

$$ {}^{EWO\ 1}_{Offset\ Vertical}T = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0.007 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

Equation 4: Computation of multi-pass offsets vertically and horizontally relative to the frames at the weldment seam level.

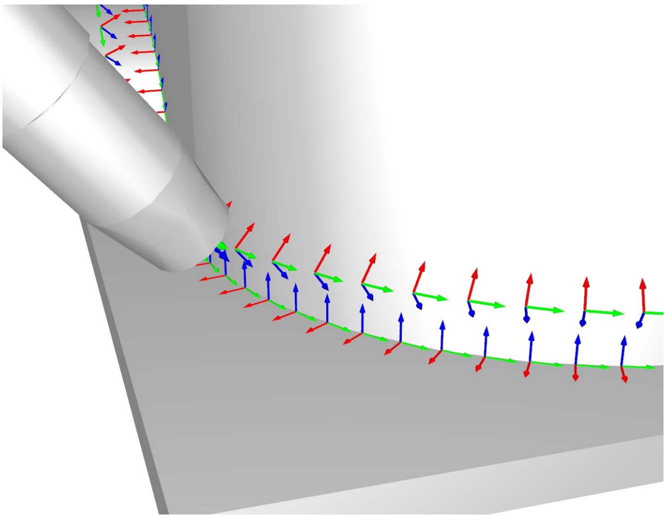


Figure 31: Example of root weldment via points, where the frames at the level of the weldment seam are also made visible.

The result of the offset translation can be observed in Figure 32, where a multi-pass program with three passes (one root pass and two filler passes) is made visible.

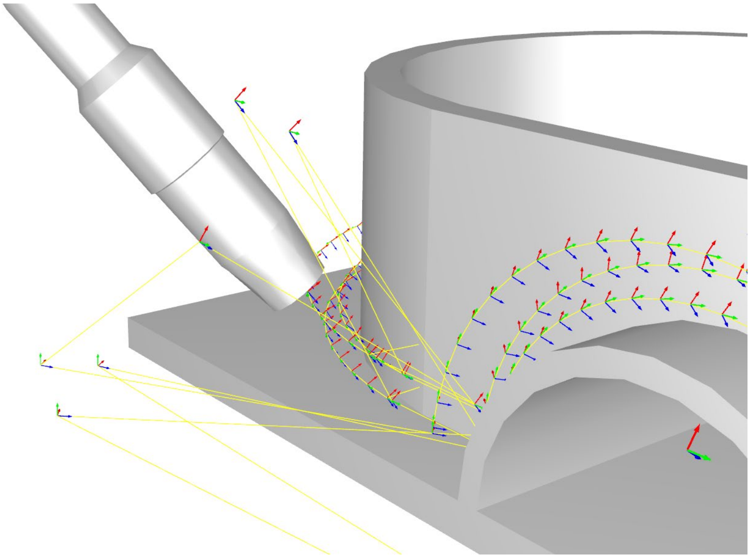


Figure 32: Result of multi-pass programming. The yellow lines are the trajectories of the welding torch as it continuously moves through the goal points. Three passes are visible for each weldment.

5.3.4. PROGRAMMING OF WEAVING

Weaving in welding is important and just as multi-pass welding, it is used to ensure that the heat affected zone will not grow out of control. To program weaving, the same principles as the offset used in multi-pass welding apply. The offset, however, is smaller and it happens back and forth with a set frequency. The weaving is controlled by the weaving frequency the amplitude of the weaving as showed in Table 9. The weaving offset is made along the X axis of the torch's goal points instead of having it along the axes of the frames along the weldment seam. However, depending on the velocity of the weldment torch and on the weaving parameters, supplementary goal points must be added to achieve the desired weaving frequency. The result can be observed in Figure 33.

By compounding the results of multi-pass welding with the weaving offsets, weaving for both root passes and filler passes can be achieved. Weaving for multi-pass welding can be observed in Figure 34.

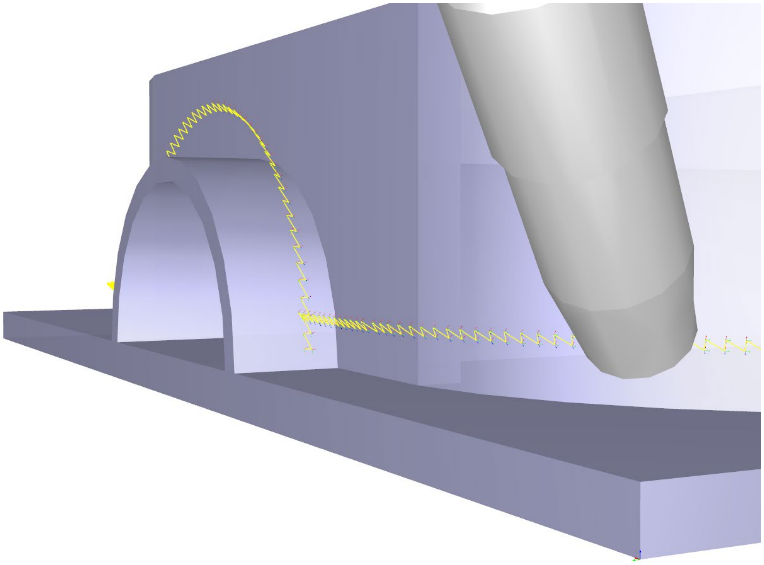


Figure 33: Weaving pattern for single pass welding. The weaving pattern is highlighted with yellow.

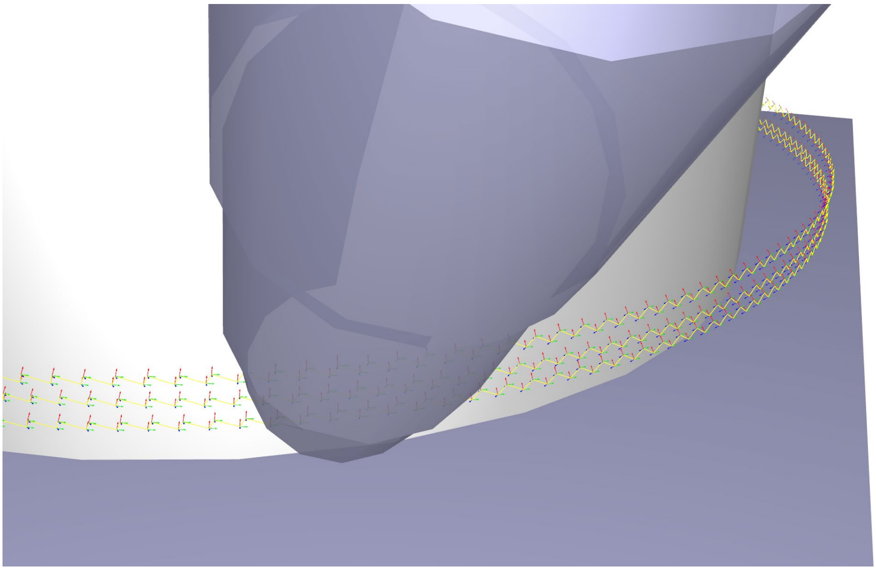


Figure 34: Weaving patter for multi-pass welding

5.3.5. TRANSFERING THE PROGRAM TO THE WELDING ROBOT AND EXECUTING IT

Having completed the import of the weldment's geometry, of arc and motion parameters and as well of multi-pass and weaving parameters, it is not possible for the generated welding program to be transferred to the welding robot. This is made possible automatically by using the RoboDK API once the programming process is completed. The prerequisite is that the welding robot is connected to the machine on which the program was generated and properly set up. The method available in the RoboDK API which makes possible the automatic transfer of the program to the robot is "MakeProgram".

5.4. DEVELOPMENT CONCLUSION AND EXPERIMENTS

The role of this chapter was to provide the reader of the thesis with further technical information about the development of the artefact which were not covered by the attached papers due to their scope. The subsections of the chapter can be interpreted as steps to be followed in order for a system integrator to achieve automatic programming of welding robots. By following the headlines of each section and subsection, the development of the artefact can be summarized as follows:

1. To Achieve automatic configuration of product models and scalable weldment annotations compliant with the ISO 2553 standard:
    a. Create a CAD model of the product which you wish to weld.
    b. Annotate the CAD model with ISO 2553 standard by using the annotations tool available in the CAD system of choice.
    c. Create design rules to allow easy scalability of the product based on the customer's requirements.
2. To extract the weldment geometry from CAD models with weldment annotations provisioned by the ISO 2553 standard:
    a. Use the CAD system's API to obtain handlers on the weldment annotations.
    b. Obtain the coordinates of the weldment edge's tessellation points.
    c. Obtain the surface normal for each of the surfaces between which the weldment is placed.
    d. Organize the weldment data under the form of Elementary Welding Operations.
    e. Digitalize the tacit knowledge of the welders to create look-up tables for the welding parameters (arc and motion parameters).
    f. Output the data extracted from the weldment annotation in a form which is interpretable by the offline programming system of choice.

3. To obtain a welding robot program, in case the offline programming system does not directly support the output data from the annotations:
    a. Use the OLP's API to import the geometry of the weldment and the proper orientations for the welding torch, relative to the welding seam.
    b. Import the arc and motion parameters to set up the velocity of the torch and the energy input for the welding machine.
    c. Program multi-weldments by using the root pass as origin, based on which the weldment paths for the filler passes can be set.
    d. To program weaving, use the look-up table built in the previous step to set up the weaving parameters. Offset the trajectory of the torch along its own X axis to obtain the weaving pattern.
    e. Use the OLP's API to generate the collision free program and to transfer it to the welding robot.

Paper IV attached to this thesis contains a software system which covers all the steps mentioned above. Since the obtained software artefact deals with

1. Product design data – the geometry of the product, the material of the product, the scalability of the product, the weldments of the product etc.
2. Process parameters – the arc parameters for welding, the velocity of the torch, the weaving parameters, number of welding passes etc.
3. Resource capabilities – programming of collision free trajectories for the welding torch on a six-axis welding robot, ensuring that every welding is reachable and others,

It can be concluded that the obtained artefact is indeed and product-process-resource model. The PPR software architecture of the presented artefact is showed in Figure 35. To validate the system, experiments were conducted:

1. At the Aalborg University's laboratory – using the RoboDK OLP:
   https://www.youtube.com/watch?v=fVslC2x6YVg
2. At FORCE Technology Denmark – using the RoboDK OLP:
   https://www.youtube.com/watch?v=A3bE_2fPkzQ
3. At Sjørring Maskinfabrik – using the Panasonic DTPS OLP supplied by Valk Welding:
   https://www.youtube.com/watch?v=hX0ZQHrMYWI

A summary of the conducted experiments and their results can also be found in Paper IV attached to this thesis (Sarivan et al. 2023b).

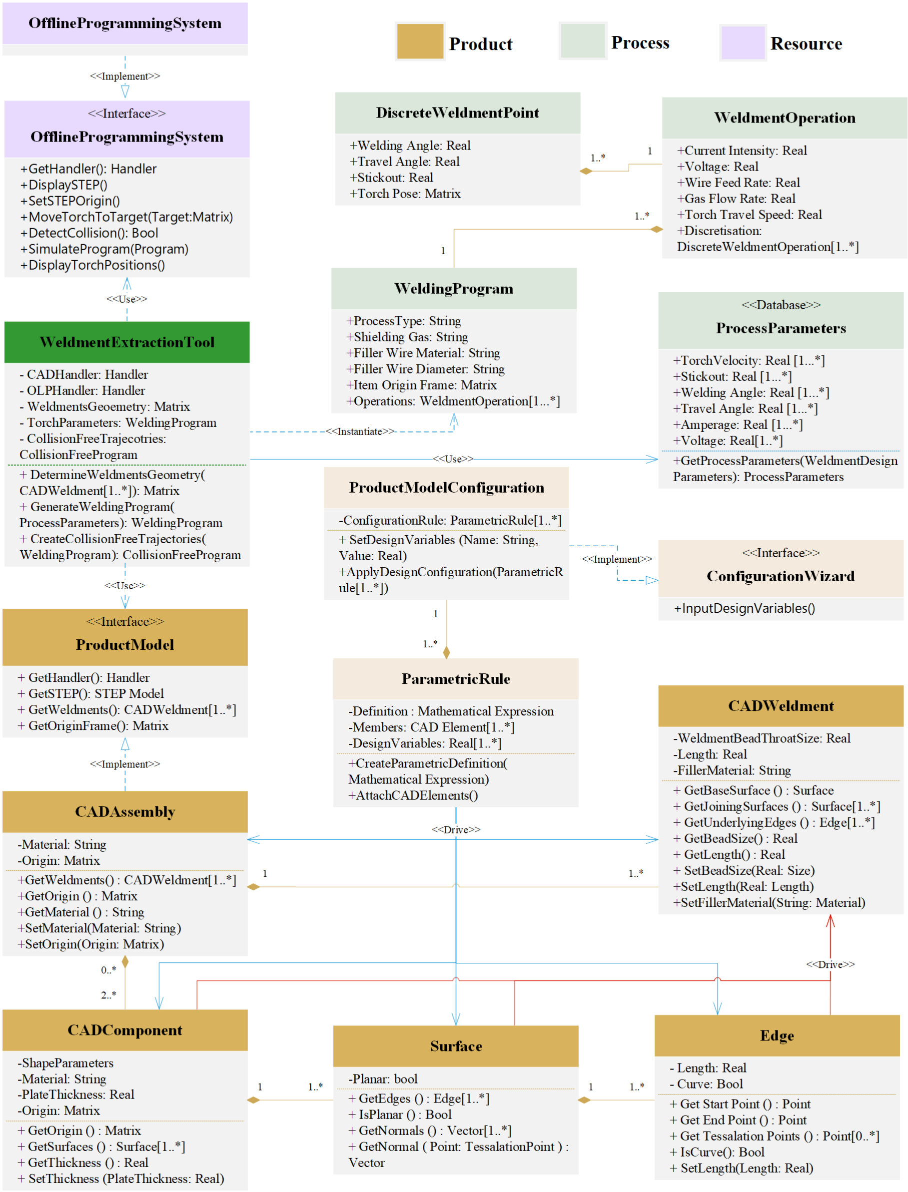


Figure 35: Overall system architecture of the automatic weldment extraction pipeline for automatic programming of welding robots based on product-process-resource models. Thorough description of the architecture is given in paper IV attached to this thesis (Sarivan et al. 2023b)

CHAPTER 6. DISCUSSION

As indicated in the state-of-the-art study of this thesis, automatic programming of welding robots is a topic of high interest for the metal fabrication industry. This topic has been heavily researched for many decades and been subject to radical developments, enabled especially by the emergence of increased computing power which makes possible the simulation of highly complex and large-scale welding assemblies inside offline programming systems.

The research presented in this thesis has at its core the design science research methodology. The main objective of this research project was to create workable results for the Danish manufacturing industry fulfilled through the relevance cycle and contribute to the field's theory in a rigorous manner. These workable results present themselves under the form of the software artefact which was presented in detail in the fifth chapter of this thesis and in the attached papers II, III, and IV. With this discussion, it is intended to bring into the reader's attention the theory implications of this research, the practical implications for metal fabricators who wish to employ automation and what is further to be done to better the artefact obtained and bring it forth to practitioners.

6.1. THEORY IMPLICATIONS

The roots of this project extend into the domain of operations management through the ever-continuous struggle of optimizing the value chain of manufacturing companies (Colli 2020). This is reflected also in the first research question of the thesis and raised in paper I attached to this thesis: "How novel technologies facilitate the revoking of traditional trade-offs between high responsiveness and high efficiency while handling high product variety, and how will this affect downstream supply chain coordination?" - (Bejlegaard et al. 2021). The assumptions made around this research question are motivated mainly by the desire to challenge the traditional trade-off between automation and flexibility where it is believed that automation will highly compromise the ability of the manufacturing system to be adapted to the customer's requirements for products. As showed in Paper I and practically proved in section 5.1, digital technologies can enable the retainment of flexibility, automate and the same time lower the competence requirements, as product configurators can be used by untrained personnel too. Regarding downstream supply chain coordination, it was observed that the bottleneck is moved downstream, and therefore operations downstream must be digitalized too. This is aligned with the observations made by (Slack 1987), that novel technology implementation initiatives should target the whole manufacturing system rather than individual operations.

To continue this journey, the programming of welding robots was targetter with the intention of automating it. As discovered in state-of-the-art study presented in the second chapter of this thesis, there is a research gap regarding how ISO 2553 compliant welding annotations can be used to automatically program welding robots. In this thesis and in papers II-IV it is showed that welding annotations can indeed be used to enable ARP and close the gap between the product design operations and production preparation operations in a streamlined and digitalized manner.

Another implication is that of using the PPR perspective over the automatic programming of welding robots. It is showed in this research that the PPR perspective is a very powerful tool for ARP applications too, and not just for pick-and-place and assembly applications as those found in literature. The concept of PPR for welding is thoroughly explored and exploited in paper IV. The final solution architecture shows that the PPR perspective is instrumental in the digital integration for automatic programming of welding robots, this being summarized with the help of the UML diagram in Figure 35.

The peer reviewed publications attached to this thesis, (Bejlegaard et al. 2021; Sarivan et al. 2022; Sarivan et al. 2023a; Sarivan et al. 2023b), fulfil the rigor cycle of this research and are aligned with the seventh thesis of DSR which states that the mission of DSR is to produce and disseminate knowledge which can be used to build artefacts that solve real problems (Hevner and Chatterjee 2010b)

6.2. PRACTICAL IMPLICATIONS

At the level of operations management, the practical implication for practitioners who intend to implement the developed artefact on their production line is described and predicted in paper I of this thesis. As it is intended to address the trade-off between flexibility and automation, the main concern which arises is if flexibility can indeed be ensured once automation is implemented. Implementing automation does not necessarily mean that the flexible way operations were being performed must be entirely removed. In the researched case-company, automation has unlocked more production capacity while at the same time reduced production cost and lead time for products which can be configured automatically, and welding-robot programs be automatically generated. At the same time, the old chain of value-adding operations was kept parallel to address special requirements from customers who wish to pay a premium to have their products further customized beyond what is possible in a configuration wizard. As presented in Figure 36, the final stage of a strategic transition towards dedicated automation is having both an ETO and an MTO value chains in parallel.

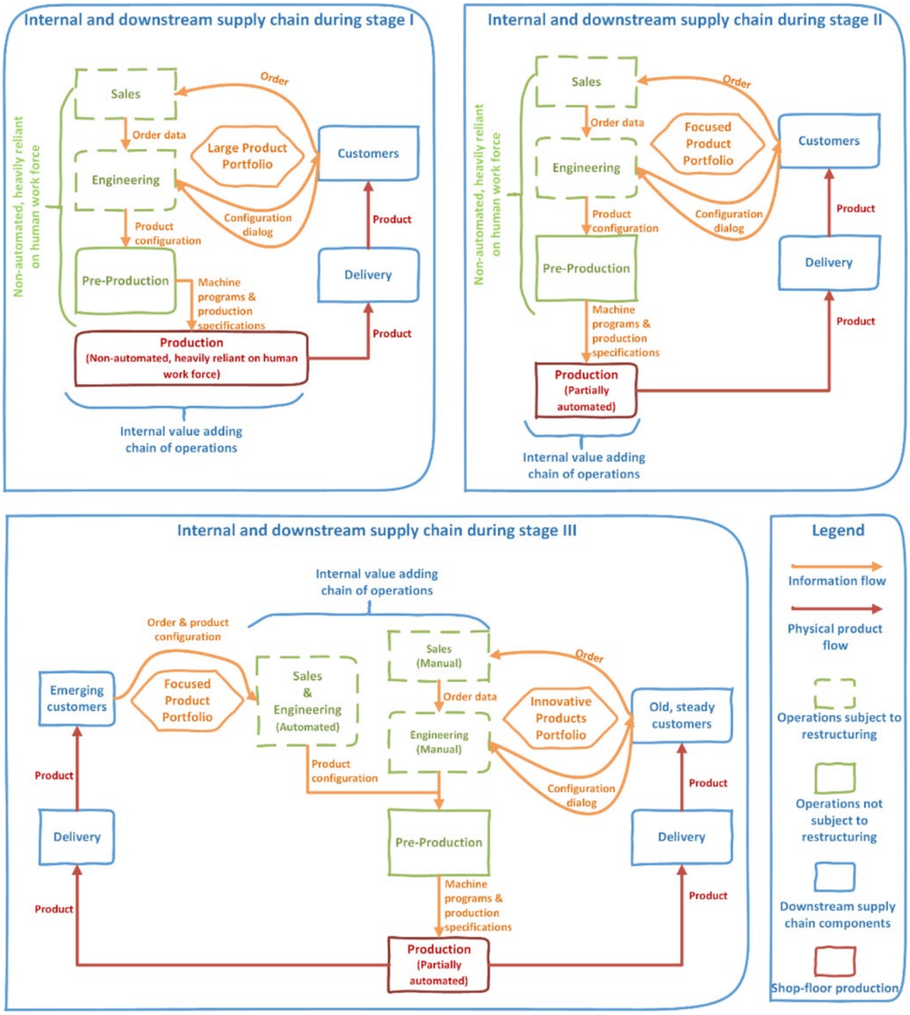


Figure 36: The strategic change of Sjørring Maskinfabrik from a complete ETO value chain, in which all products were made based on the customer's requirements, to dedicated automation for emerging customers (MTO) while keeping a high level of flexibility dedicated to high-paying customers (ETO) in parallel (Bejlegaard et al. 2021).

After the presented artefact was implemented on the value chain of the case-company, it was observed that redundant digitalisation efforts have been eliminated. Namely, once the weldments are annotated on the product model, it is no longer needed for the robotics engineer to program the geometry and the welding parameters in order for the robot to perform the welding. The old process of manually programming all the weldment related information inside the OLP is illustrated in Figure 18. The new digital integrated process for automatic programming of welding robots is illustrated in Figure 37. All the weldment related information can now be imported automatically inside the offline programming system by using the ISO 2553 standard.

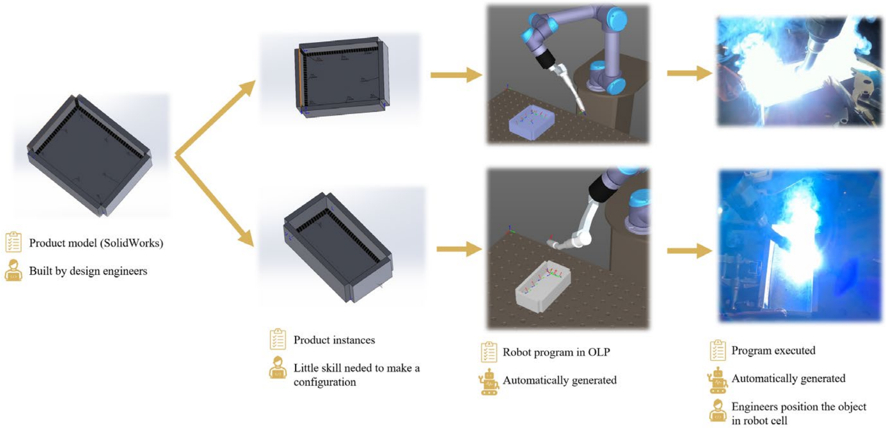


Figure 37: New digital pipeline for automatic programming of welding robots: the product is scaled up or down using configuration wizards and the weldment information is automatically imported inside the OLP.

Automation of programming of welding robots impact the production preparation operations and the production operations by increasing the usability rate of the welding robots. As reported by the case-company following the implementation of the presented artefact in this thesis, the time required for programming of welding robots is drastically reduced from a few days to a few minutes. However, it was mentioned by the engineering manager at Sjørring Maskinfabrik that the artefact can automate the programming of 80% to 90% of their weldments and the rest need manual intervention still due to errors at the level of the ISO 2553 weldment annotations. This also suggests the need for further research and development to mature the artefact and make it fully viable for use in the industry.

6.3. FURTHER RESEARCH AND DEVELOPMENT

However, as explained by (Hevner et al. 2004), design science research is perishable. This means that at the very time of writing this thesis, the presented research results may have already been rendered obsolete by the fast technological development of our times. Nevertheless, through continuous research and development, the artefact presented in this thesis is expected to reach a stage mature enough to be successfully used in the industry.

Backed up by the state-of-the-art study, it can be stated that the approach towards automatic programming of welding robots is novel as it exploits the ISO 2553 weldment annotation and involves the PPR perspective on the programming process of welding robots. Both of these approaches were never used before in the studied literature, nor it was found to be used together in practice. However, the novelty must be accompanied by thorough testing and validation in the industry. So far, the artefact was tested in controlled and semi-controlled environments at Aalborg University, FORCE Technology and Sjørring Maskinfabrik using test products or only the products provided by the case-company. It is therefore necessary to inform the reader that a certain level of bias may be present in the research results due to lack of testing from a third independent party. Therefore, subject to further is research is the through testing of the artefact together with an independent party. This testing should also be carried out by using products of varying complexity and geometry.

The research presented in this thesis and in the attached papers was focused solely on the automatic programming of welding robots. However, even though a complete welding program is obtained, there will always be a mismatch between the virtual model of a product and its real counterpart and therefore a mismatch between the programmed welding trajectories and the real product's welding seams. This is due to various fabrications errors and the forming properties of the materials. These offsets are traditionally handled through touch sensing, as described in section 1.4. The implementation of touch sensing is handled automatically by the software provided by Valk Welding within the implementation which used DTPS as OLP. However, the implementation of touch sensing using RoboDK OLP has been briefly undertaken in this project but not finished. Therefore, a next step as further research and development is to investigate the hybrid programming of welding robots which uses both information from CAD models and information from various sensors that can be installed in the welding cell, as described in subsection 4.1.2.

The artefact presented in Chapter 5 is meant to digitally integrate CAD systems and OLP systems to prevent the manual transfer of data between these two systems. Acting as a platform which supports the digitalization of tacit knowledge, the artefact further brings value by having activated knowledge present in the organization, but which otherwise could have only been used in a manual manner by the welding experts. By using the artefact, it is possible for the design engineers to indirectly set up the welding process by specifying the design parameters related to the product. The PPR perspective, thus brings together product design knowledge from design engineers, tacit process knowledge from welding experts and resource knowledge from robotics engineers under one unified platform.

Currently, the artefact can only handle the SolidWorks CAD system and the RoboDK OLP and the DTPS OLP supplied by Valk Welding. Therefore, it is intended as further development to create support for the rest of CAD systems which can handle weldment annotations compliant with the ISO 2553 standard. Some of these systems are AutoDesk Inventor, Siemens NX, Creo and SolidEdge. The same applies to offline programming systems. Further development is intended to be carried out to support offline programming systems from Kuka, Fanuc, ABB, FastSuite, and Visual

Components. An overview on the current state of the artefact and the support subject to further development is provided for the reader in Figure 38.

To ensure the quality of the weldments, the workpiece must be secured in place to prevent offsets caused by the metal expanding due to heat input. The research and development into flexible fixtures are highly relevant when dealing with one-of-a-kind production.

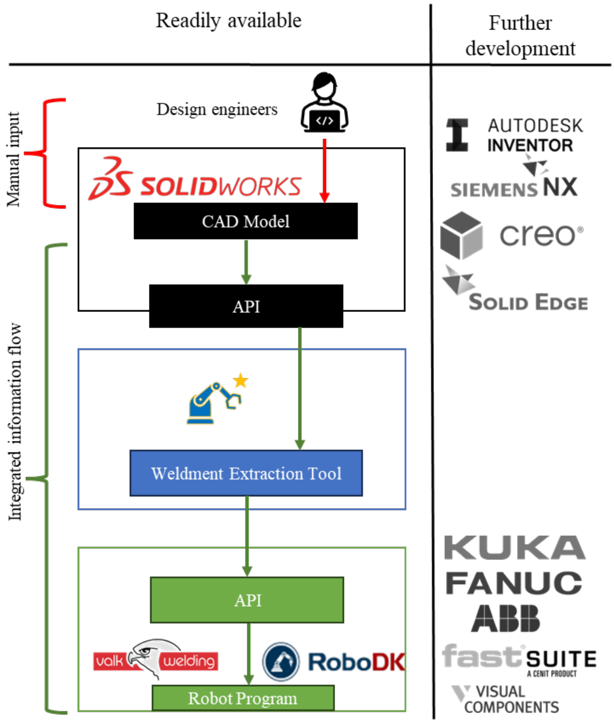


Figure 38: Current state of the artefact and further development meant to provide support for further CAD and OLP systems.

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CHAPTER 7. CONCLUSION

This Ph.D. thesis was written with the purpose of tying together the findings presented in the attached papers and inform the reader how the design science research methodology was applied to come up with the presented results. The Ph.D. project was motivated by the current situation in high-cost environments in countries like Denmark, where technological advancement is found to be one of the few solutions in the attempts made by SMEs to remain competitive on the global market. Hence this project was conducted as part of the MADE innovation cluster which has as purpose to bring together Danish universities, RTOs, and SMEs in order to bring the Danish industry at the highest technological level possible.

By establishing a knowledge base through literature studies and by investigating the state of practice at the case company, both the rigour and the relevance cycles were able to be conducted. The rigour cycle addressed research gaps in the field's literature while the relevance cycle addressed the need of the case company to increase the utilization rate of their welding robots, lower production cost and reallocate valuable human resources towards expanding the business further. During the design cycle, the artefact supporting the relevance and rigour cycle was developed in collaboration with the case company and technology suppliers.

The reader was provided with further details about the welding process and the operations around beyond what is contained in the attached papers. Special emphasis was placed on the state of practice at the case company and details about the case company, how the DSR methodology was applied in this research project and further technical implementation details for the product configuration wizard, the extraction of data from ISO 2553 annotations and the data import process for RoboDK.

Beyond the collaboration with the case-company within the MADE innovation cluster, the developed artefact attracted significant attention from other companies involved in the metal fabrication industry too. This is taken as sign regarding the relevance of such value chain digitalization and optimization efforts as the one presented in this thesis. The researcher will attempt to mature and commercialize the presented artefact in order to make it widely available for the Danish industry.

LITERATURE LIST

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PAPERS ATTACHED TO THESIS

SUMMARY

Small medium enterprises located in high-cost environments like Northern Europe, are increasing their reliance on digitalization and robotics to lower production costs and to keep the competitive edge over companies in low-cost environments. Using and developing technological methods shows that a high degree of flexibility is kept by digitally integrating manual labour and ensuring seamless end-to-end information flow across the internal and downstream supply chains. Thus, the concept of a product-model is proposed which congregates the design, engineering, and pre-production information about the product itself and the manufacturing system, in the context of steel welding industry. The necessary research and development are conducted through several design science cycles to ensure both the relevance of the proposed concept for the studied case company, and the rigor of the contribution to the knowledge base in the field. It is intended through the implementation of product-model based technologies to eliminate the need for manually conducted pre-production operations e.g., welding-robot programming, and radically reduce the time needed for pre-production operations.

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