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Analysis of a robot welding system and possible concepts for improvement for a Norwegian SME

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Preface

This is a master's thesis in the study program "Master in Sustainable Manufacturing" at NTNU in Gjøvik. It has been carried out in collaboration with Tokvam as and is about the analysis of a robot welding system and possible concepts for improvement.

The research has been carried out in the winter semester of 2019.

The assumed background of the readers of this report lies in the field of robotic welding and industrial manufacturing.

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Thank you to my family and friends, for all the fun and motivation you shared unknowingly.

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L.K.

Abstract

The production of commodities in Norway requires a well designed production system, able to cope with customer requirements and challenges induced by the economic standards of the country. Customers require high quality products to be delivered fast that suit exactly the needs of the job that has to be carried out. Economical challenges in these regards come from the high cost of labor, which means buying manual labor for the sake of flexibility is not a permanent solution. It can be used as a measure to increase flexibility and throughput for a limited period, but cannot be economically feasible permanently.

Tokvam AS is such a company, employing less than 40 people and being located in central Norway. The products are attachments for tractors and other carrier vehicles for road maintenance mainly in winter but also in summer conditions. Ranging from snowblowers over salt- and sand-spreaders, snowplows to sweepers, Tokvam can provide a product portfolio to its customers that covers all the essential tasks when ice and snow (and the residues after the winter season) need to be removed or treated for traffic to function. The large portfolio requires a production of attachments in many different sizes and variations, additional equipment and spare parts. To be able to deliver all those with short lead times, in high quality and for good price while still remaining competitive requires for that production to be automated where possible.

This thesis follows the analysis of a part of the company's production system, a welding robot used for producing smaller machine parts, which is not able to produce up to the varying demand. Due to long changeover time and problems with the logistics of jigs and fixtures, manual welding is still the preferred method for some components. Two alternative robot welding systems to replace that welding cell have been suggested, replacing the cell is one strategy which the author discusses. Further, during the research the author found flaws in the current organization of welding jigs and fixtures as being used in the affected robot welding cell. The influence of these factors that lie outside the welding cell's system was examined as it offers another concept for improving the welding- and production system. A third possible alternative, a hybrid work space for manual and robotic welding, was discovered during the project. In addition to being a way for automated welding of small-size, large-volume parts this option has the secondary value of introducing a collaborative human-robot environment using amongst others sensor-assisted teaching. The author discusses the opportunities and possible drawbacks of this rather low-cost solution.

The thesis concludes with the suggestion to opt for two of the proposed solutions to solve the current problems: systematically organizing and integrating jigs into the ERP system and investing in the hybrid welding system. The author discussed the risks and opportunities of all proposed solutions and these two promise to yield improvements in most of the problematic areas. At the same time the hybrid system can be a stepping stone for Tokvam to develop further towards human-

robot collaborative manufacturing systems. Further, the financial effort connected to implement the proposed improvements is significantly lower than the one for the other proposed robotic welding systems.

Contents

List of Abbreviations

CAD computer aided design

DIN German Institute for Standardization

DOF degrees of freedom

HRC human-robot collaboration

ISO International Organization for Standardization

MAG metal active gas

MIG metal inert gas

NTNU Norwegian University of Science and Technology

SINTEF The Foundation for Industrial and Technological Research

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1 Introduction

While sectors like the oil and gas industry, fishery and the energy-intensive production of aluminum make up a large share of the Norwegian industry, the industrial production of commodities is not one of the industries one thinks of first when considering the high-wage country. Unlike the other named industries, there seems to be no unique reason to produce industrial goods in a location where labor cost are higher than elsewhere. While the process industry and fishery are enabled by the factor of Norway's geographic location and the aluminum production benefits from relatively cheap energy from renewable resources, there is no self-evident reason to manufacture in Norway.

This may apply to machines in general, cars or other commodities. On the other hand the manufacturing of equipment for road maintenance – especially in winter conditions – is an industry which benefits from several, not only geographical, circumstances providing reasons for manufacturing in Norway. May it be the close relationship that manufacturers can maintain, being situated next door to the end-users, customers and distributors, or the environment for testing products. Or the challenge of developing a product, which by today requires a human operator to be as effective as possible to make the human-oriented service of road maintenance effective today and in the future.

While the reasons for manufacturing in Norway are not a subject of this thesis, the way of manufacturing is. The apparent challenge of high cost of labor pushes manufacturers to optimize their production systems constantly, in order to compete locally and globally. Knowing where to begin this optimization in the production system and how to leverage the mix of available internal expertise and funding in the right way requires a thorough investigation of the overall system. The company Tokvam is such a manufacturer, producing road maintenance equipment in Norway. Supplying equipment for many different jobs of road maintenance both in summer and winter, Tokvam chose a product mix of large variety to be a holistic supplier for its customers. Approximately 40 employees – of which the majority works in the production department – strive to develop and produce equipment to meet and exceed the customers' expectations. The internal competence which developed during over sixty years in the business is constantly enriched by collaboration with Norwegian University of Science and Technology (NTNU) and The Foundation for Industrial and Technological Research (SINTEF) for training and development e.g. in projects to achieve a more effective production or develop more effective products and through acquisition of highly skilled employees. The company used two welding robot cells in order to automate the – before – completely manual welding of chassis and components of its products. This marked the first step of improving the production system's effectiveness by automating one of its parts to a certain extent. The two robot welding cells of different sizes are located in the plant's welding department. One of them, welding mainly large parts like chassis, is utilized almost to its maximum capacity while the other's potential is not fully used. In fact, many of the small components that could be welded using the smaller robot welding cell are still produced manually instead.

1.1 Research problem

The under-utilization of the small robot is problematic and has several reasons. One reason why the equipment is rarely used, is because the setup time is rather high in comparison to effective production time. This is especially inefficient when producing in a small batch size due to the even higher amount of setup-changes. The challenge that Tokvam is facing is induced by the customer demand and product strategy as touched upon in the previous section and as will be described in detail in section 4.2. In the current state, the system is vulnerable when the demand increases and is causing waste due to unused potential already. Therefore, an investment in replacing the affected robot cell with a system that can handle the rising variation and at the same time can be operated in a more efficient way was planned. Yet, finding and choosing the best solution is a challenge for the company. In this thesis, multiple possible solutions will be discussed which include replacing the robot welding cell and enhancing the system's capabilities in various other ways. The following research questions were guiding this research project and reflect the way it developed from originally searching for the best replacement of the cell, over recognizing other systemic errors to finding alternative solutions through a systematic analysis.

1.2 Research question

The current robotic welding system is under-utilized which means that too few components are welded automatically and manual welding is currently used to compensate that loss. The following research questions give an outlook on different strategies for solving this problem:

RQ 1: What robot welding systems can be found to replace the current cell and solve the problem of under-utilization and which risks, challenges and opportunities are connected to the different systems?

RQ 2: How do other parts of the production system contribute to the problems of the welding cell?

RQ 3: What are possible alternatives to replacing the cell, that can lead to more components being produced automatically?

1.3 Structural outline

The following thesis is structured as follows:

Section 2 describes the methodological approach to the research. The author further presents the concept of systems thinking and the progression of the work from a methodological standpoint.

Section 3 presents the fundamental theory of welding and the impact of product variety on production systems.

Section 4 describes the current state of Tokvam as a manufacturer of a variety of commodities, the manufacturing system and the robotic welding system. In this section, the correlation between products, customers and the manufacturing system becomes apparent.

Section 5 provides insight into the possible solutions that can be implemented to solve the problems which Tokvam is facing currently and which might become even more challenging in the future.

Section 6 discusses these solutions in the context of contemporary research and the risks and opportunities that go along with each.

Section 7 concludes the thesis.

2 Methodology

In the following chapter, the author will present the methodological approach of the thesis. The research was conducted with the concept of transferability in mind, which is described in the first section. Another fundamental concept was the notion of systems thinking which will be introduced before the author presents the actual methodological approach of the thesis. The chapter ends with a review of the (methodological) progression of the research project, where the author describes the way from a quite analytical beginning towards reaching a more systemic perspective on both the technical system and the human component of the company.

2.1 Validity in qualitative research

Qualitative research typically focuses on "real world"-phenomena and rather aims to study their complexity rather than simplifying the observations. Usually, where little is know about the phenomenon, qualitative research is the methodology of choice, which in an iterative process moves between collecting data and analyzing it in order to explore the phenomenon (Leedy & Ormrod 2015).

This methodology has potential advantages, when the purpose of the research is to: explore a little studied topic, describe a system it in its complex nature, test the validity if certain assumptions in real-world contexts and to evaluate whether a chosen solution is effective or not Leedy & Ormrod (2015).

As shown by Ritchie & Lewis (2003), qualitative research may be rather judged by its transferability (or also commonly referred to as generalizability) than external validity. How the results from this thesis may apply to other, similar cases was of important for the author. Especially with regards to other businesses of similar size and within the nordic countries, transferability can be ensured as long as company culture is not left out of the equation. As described before, the company and most of its employees grew together in the recent years, developing their own means of communication, decision making and managing production. How that influences a project like that cannot be generalized and needs to be assessed individually.With regards to the aforementioned transferability of results, the researcher can only understand which data to collect and in which manner to collect it to benefit transferable results, if he understands the project in its environment.

2.2 Systems thinking

Arbnor & Bjerke (2008) distinguish three different methodological views on how knowledge can be created: the analytical view, the actor's view and the systems view.

In the analytical view, interrelations between subjective facts (which can be influenced by opinion) and objective facts (which are not influenced by opinion) are not taken into consideration. In a model constructed from the sum of these facts, they are treated equally in the context of knowledge creation, which makes this view rather useful for explaining those facts rather than their interrelations (Arbnor & Bjerke 2008).

The actor's view treats the knowledge-creator as an inseparable component of the reality under investigation. While objectivity is required in the analyitcal- and systems view, the actors view claims that such objectivity is impossible. The knowledge creator never exists independently of the system and his actions affect the environment he aims to understand. Assuming that objectivity is an idealized state which is impossible to achieve, the knowledge-creator necessarily must also be part of the creation of reality in order to reach an understanding of the studied objects (Arbnor & Bjerke 2008).

The systems view is based on the paradigms of systems thinking, where in contrast to the analytical view, the interrelation between the parts matter and a holistic view on the system is supposed to be achieved. The system under investigation shall be understood in its complexity which means that none of its parts can be analyzed in isolation, neither can the system be understood without the context of its environment (Arbnor & Bjerke 2008).

Systems thinking is this distinct methodological approach, that means understanding components of a system as interrelated, influencing each other and working together to transform inputs into outputs. Commonly, the analogy "a system is more than the sum of its parts" is used to describe how a goal can only be achieved by the correct interconnection of the components in a system (Edson 2008). While a system has boundaries, inputs and outputs define its interface to the outside world, which Arbnor & Bjerke (2008) call the environment. The environment in an open system is crucial to consider for the system's performance, yet it is beyond its control. It depends on the researcher how to investigate a system, whether to study it as a closed system (isolated from its environment) or as an open system (in the context of its environment) (Arbnor & Bjerke 2008).

When modelling such a system, the researcher has to act according to the contribution intended to deliver with the research. If the model is meant for descriptive purposes, a detailed model can be created. But if the model is intended to be used for possibly changing the real system afterwards, it needs to be designed usable, not overly complicated. Thus, details may need to be disregarded (Arbnor & Bjerke 2008).

The level of detail is determined by the magnifying level which is used. For this thesis the author uses different levels, which are referred to as the "production system" (which includes welding, assembly, painting and all other supporting processes) and "robotic welding system" which is nested in the environment of the production system. While the production system is treated in less detail but still important to consider in many regards, the robotic welding system is what is really aimed to be magnified in this research.

2.3 The methodological approach of the thesis

The specific case of this thesis – i.e. the analysis of a robot welding system with the goal to find a solution for improving its performance – was supplied by Tokvam and the whole thesis was carried out in close collaboration with the company, most of the time on site. This enabled the author to examine a complex industrial case in detail. As Leedy & Ormrod (2015) state, it is crucial to be present on site as much as possible if a researcher wants to claim being able to reach an understanding of a complex problem and to reach valid conclusions.

The socio-technical system – highly influenced by the workforce that in great measure grew together with the company's development in the recent years – offered a challenging environment for research with lots of opportunities, also for future work. Past and current collaborations of Tokvam with student research projects from NTNU and SINTEF about amongst others engineering design and production engineering show the same pattern. The goal was to find a solution for a real-life problem, related to the case of Tokvam. This means that not all results from this research can be unconditionally generalized and applied to other cases without further work. Choices were influenced by the above mentioned socio-technical system and this needs to be considered when transferring the findings to similar cases.

2.4 Progression of the research project

This thesis originally started off on the following premise: A robot welding system is not performing well in the way that it is being utilized in the current state. Based on that, suppliers for alternative systems were contacted and, by observing reference cases, ideas for alternatives were gathered. The author joined the project at a stage where suppliers have already been contacted and several solutions to replace the welding cell have been proposed. He then followed up on those proposed solutions by visiting companies employing similar systems for reference and stayed in contact with the suppliers. Further, information about the state of the art in robotics and automation was gathered by visiting trade fairs and the suppliers. The research meanwhile progressed along being focused on possible alternative welding systems and theory about automated, yet flexible manufacturing systems. The correlation between what is required by customers (end customers as well as downstream processes within the company) and the requirements of manufacturing systems played an important role in this first phase of the research.

Later on, the author worked closely together with the workers on the shop-floor in order to catch what they observe when working with the current robot welding system. This revealed information about the performance of the system which cannot be obtained by plain data analysis. Problems in the logistics and with other supporting processes were found. Understanding how complex the system is and how other processes must be working well for the robot welding process to perform properly, enabled the author to broaden the perspective on the topic. This influenced the progression of research in the way that in addition to thoughts about an investment in a new robot welding system, also considerations about the logistics of jigs became important.

From the original thought of assessing the benefits of possible new robot welding systems, the author proceeded with assessing other improvement strategies as well. This required to spend more time on site in order to gather detailed information about the current state and its drawbacks. Combined with what contemporary research has to offer by e.g. means of human-robot-collaboration, the thesis progressed towards more creative solutions than solely replacing the current robot welding cell. What started off as a very analytical approach, which was meant to find the best replacement for one part of the manufacturing system, turned into a perspective on the larger socio-technical system. In the latest stages of the research project, the possible secondary impacts of what was found to be the best solution to the problem were unveiled. The author found opportunities for the company that go beyond replacing a weak link in the chain and more towards the introduction of advanced means of manufacturing, considering aspects for extending the internal competence.

For discussing the solutions as presented in this thesis, the author relied on contemporary research and analyzed the proposals in context with the production system which they need to fit into after all. For finding relevant and literature, the author used the databases of Web of Science, Scopus and ScienceDirect. Search filters to avoid outdated material and to focus on finding papers from peer-reviewed journals were used for most of the material. Exceptions were made for standard references on manufacturing technology, which were consulted to provide the reader with insight in welding technology and not for discussing the found solutions in contemporary context.

3 Theory

The author will use the following chapter to introduce to the principles of welding, for the reader to understand the concept and scope of the manufacturing technique. Two welding principles are going to be explained in more detail because one (gas welding) is the one probably easiest to comprehend for readers outside the subject and the other (arc welding) is the one applied in the presented case. Further, the impact of product variety on production systems will be shown.

3.1 Welding

Welding is classified as a manufacturing technology for joining materials by the German Institute for Standardization (DIN) (DIN 2003) and qualifies as an assembly technique which

> "makes it possible to reconstitute metallic continuity between the components to be assembled. This reconstitution involves the re-establishment of the interatomic metal bonding forces which requires at the same time a connection of the nodes of the crystal lattices and the absence of any foreign body likely to constitute a screen."

(Blondeau 2008, p. 1). It is therefore crucial to provide for certain conditions when welding is chosen as an assembly method. To provide for these conditions, a set of established welding technologies developed since the latter half of the 20th century that are used in industry nowadays. Welding is one of the most common application of robots in industry (Lin & Luo 2015) and constantly improved by applying new (sensor) technology.

Compared to other assembly technologies like screws, welding cohesively bonds the joined materials and welded joints cannot be disassembled without destroying the material. The process induces changes in the crystal structure of the joined parts close to the welded area as well as tension in different directions, which requires for adequate construction design before and dimensional control afterwards (Fritz & Schulze 2012). As it is mostly the case, the negative side effect of warping material is prevented by using jigs and clamps. Preventing poor mechanical performance of the welded product due to the changes of its crystal structure requires an experienced welder, knowing where and how to place the weld seams.

In return, an welding system is less costly to automate than an assembly system for force-fitted joints (bolts, rivets, etc.) and at the same time more flexible. The joining partners are welded edge to edge, while a bolted or riveted connection requires additional, overlapping material. Usually a tool change within a welding process is not necessary and welding-parameters like voltage, current and feed rate can be adjusted during operation, e.g. if a product consists of parts with different material thickness.

3.2 Welding technologies

When choosing the right welding technology for an application, there are many factors to consider given the multitude of available technologies (Fritz & Schulze 2012). Fritz & Schulze (2012) further point out, that the material determines the optimal welding conditions of choice, which includes both the used technology and the adjustment of welding parameters (e.g. electrical current, voltage, feed rate, etc.). Other determinants of the chosen welding technology are what kind of parts are being welded (i.e. geometric nature), production volume and general conditions for manufacturing. Finding and using the optimal welding technology for all these circumstances is in reality rarely achieved. Often, economic restrictions and the integration of existing systems lead to searching for feasible compromises that satisfy as many as possible of the given requirements.

The International Organization for Standardization (ISO) presents a framework for nomenclature of all the welding processes which are divided in six main-groups. The processes can be divided further into groups and subgroups and even after that there are further possibilities to specify, e.g. by the use of additional filler material, different transfer modes and the combination of processes (hybrid-processes) (ISO 2010). The six main groups vary in the way that energy is provided to join the parts, further the groups specify means of protecting the molten metal by use of gases and powders. The possible choice of filler material and further specification of energy input provides for the differentiation into subgroups (Blondeau 2008). The six main-groups, respectively welding techniques classified by ISO (2010) are:

- arc welding,
- gas welding,
- resistance welding,
- welding with pressure,
- beam welding and
- other welding processes.

Arc welding and gas welding will be described in detail in the following two subsections. Gas welding can comprehensibly depict the principles of welding in general and arc welding is the technique in use for the current research project.

3.2.1 Gas welding

Blondeau (2008), Fritz & Schulze (2012) and Spur & Stöferle (1986) describe gas welding as follows: Gas welding uses the flame of a blowtorch as input energy to melt the edges of the parts to be joined. Inside the blowtorch a combustion gas and oxygen are mixed, usually in a 1:1 ratio using acetylene as combustion gas for welding most materials. The ignited flame reaches a temperature of 3400 K in the welding area and has a reducing atmosphere. The molten metal is protected against chemical reactions with gases in the surrounding air by that atmosphere (similar to the protecting function of powder, gases and coating used in arc welding techniques, see subsection 3.2.2). Increasing the volume ratio of oxygen to acetylene gas makes this technique suitable for welding brass (the oxidizing flame prevents zinc-evaporation), increasing the volume of acetylene provides for a carburizing flame, suitable for welding cast iron. Filler material can be added to the welding pool in form of rods of the respective material, a flux to reduce surface oxidation when welding aluminum, stainless steel or copper alloys can be added as well. Gas welding is therefore very adaptable to the required scenario.

This technique is performed manually with the blowtorch being handled by the welder in one hand and filler material being added with the other. The nature of the flame provides a rather large area of heat-influence on the material, thus warping of the material is very likely. Further, the comparably imprecise energy input of the flame makes this technique less suitable for welding thick material (thickness > 8 mm) since the energy is not as concentrated as in e.g. arc welding techniques. What sets this technique apart from others, is the possibility to control heat-input and filler material independently. This makes gas welding suitable for weld cladding, welding of very heat-conductive material (e.g. copper) and welding in constrained positions. On the downside, this feature makes the technique unsuitable for automation and requires a highly-skilled operator to control and adjust all the mentioned parameters simulatneously.

3.2.2 Arc welding

Blondeau (2008), Fritz & Schulze (2012) and Spur & Stöferle (1986) describe arc welding as follows: Arc welding is a principle that is used in different welding techniques, which again use different principles for protecting the welding process from atmospheric influences. The most common techniques are manual metal arc welding, submerged arc welding and gas-shielded metal arc welding. The energy to melt the joining partners and filler material comes from a light arc between an electrode and the welded material. A light arc is a current-carrying conductor, initiated by a short circuit between the electrode and the work-piece. The arc is kept stable by easily-ionizable elements provided by the gasses or solids supplied to the welding processes and a functional interaction of the parameters of the power supply.

In manual arc welding, the electrode is covered with a coating to protect the welding process from atmospheric influences and to provide easily-ionizable elements to keep the arc stable. Similarly, in submerged arc welding, a powder – under which the welding process takes place – provides for these functions. In gas-shielded metal arc welding a mixture of gases protects the weld pool and keeps the arc in a stable condition.

3.3 Product variety and the impact on production systems

Wiendahl et al. (2007) introduce to the modern challenges affecting manufacturing by recalling the inside and outside factors which require industrial production systems to adapt. Internal factors are amongst others the products, and methods and technologies in use, while markets demand adaption from the outside. The market demand, caused by customer behavior, affects e.g. life cycles of products, requiring fast change and constant improvements of products. This increases the number of products on the market and means increased complexity in production for the manufacturer.

Predicting the behavior of the market is challenging and thus, the production volume of each product variant cannot be estimated easily either (Hu et al. 2011). This means, in order to cope with the unstable demand the manufacturer has to increase the volume flexibility as a measure to prepare for those changes in manufacturing. The easier and the more profitable a manufacturer can adapt to different demand scenarios, the less he is affected by the changing demand (Hu et al. 2011). To achieve that, scalable manufacturing lines can increase the production system's ability to react to volume changes by adding, subtracting or changing the system's components. Increased convertibility provides means to change the production system according to e.g. new product types (Hu et al. 2011). Both need to be considered when investing in new equipment Fernandes et al. (2012).

Rudtsch et al. (2014) argue for a close interplay when designing products and production systems. The closer the collaboration between product engineering and production system engineering is in the early design phase of a product, the better the production system can serve criteria as flexibility, thus variety and quality of the final product. What can be challenging in this design phase of a production system – and when acquiring new production equipment – is how to measure the benefit of flexibility compared to e.g. productivity. Flexibility is harder to measure and express with monetary values, thus high initial cost of investment does not return as well for flexible equipment than for productive equipment (Fernandes et al. 2012).

4 Analysis of the current state

4.1 Tokvam: a Norwegian SME

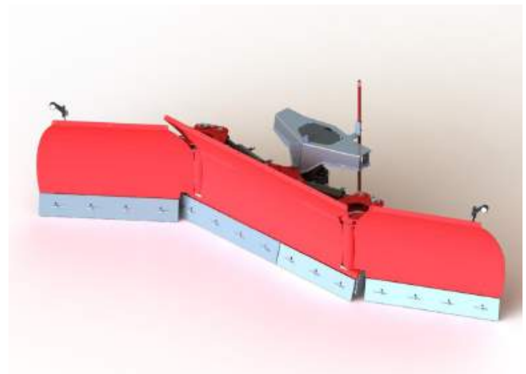
Tokvam is located in Norway with its production facility employing circa 40 people in manufacturing and administration. The location of the company can be considered demanding with respect to the high cost of labor in Norway. Strong competition in the market sets high quality requirements to the products of Tokvam in order to keep a competitive advantage, which adds to the list of challenges. Innovative products are key to stay ahead of competition and one of the competences that sets the products apart from others.

A progressive focus on product development in close collaboration with customers and research – for example NTNU in Gjøvik – enables the company to benefit from its location in Norway. Being closely located to Tokvam's largest market, the company can test, improve and develop its products under real life conditions.

4.2 Customers and products of Tokvam

Customers in the snow and ice removal and road cleaning service industry need a wide variety of products to operate their businesses. Depending on weather conditions, the customers of Tokvam AS require equipment for different tasks that works reliably with the carrier vehicles they use. The company's goal is therefore to "make winter easy" (Tokvam 2018, p. 3) by providing flexible and effective, high-quality equipment that is easy to use. In addition to that, providing products not exclusively for the winter season like sweepers, Tokvam strives to "make year round maintenance easy" (Tokvam 2018, p. 23). Being a holistic supplier for everything that is necessary to remove snow and ice and to clean roads independent from the brand of carrier vehicle, products suitable for the following vehicle classes are produced: tractors, wheel loaders and compact machines. Inside these classifications one finds equipment for different applications and in different variations of size and features to cover all scenarios and seasons.

Snowplows are used to remove snow from e.g. roads with high velocity, using the shape of the plow to both scratch the snow off the surface and throw it to the roadside (V-plows). Other variations (U-plows) are used for rolling large amounts of snow to the side, e.g. on parking lots, benefiting from working widths up to 490 cm. Hydraulic controls enable the driver to adjust the shape and orientation of a plow without leaving the cabin. Thus, both plow types can be adjusted to the specifications required by the purpose.



(b) U-plow

(a) V-plow

Figure 1: Two different principles of snowplows

Snowblowers are the product of choice for removing wet, heavy snow. Being mounted to a carrier vehicle in different orientations they are either pushed (rear or front mounted) or dragged (rear mounted). Blowers working after the two-stage principle use an intake auger to transport the snow inside the machine, where it is collected and blown out through a chute by an impeller. V-shaped blowers can only be dragged and use the v-shape and feeding vanes to transport the snow inside the machine instead of an intake auger. See figure 2 for the differences in the design of those two principles for snowblowers. Thanks to the impeller and chute, snow can be thrown much further with a snowblower than when rolling it with a plow. Using loading chutes enables transporting snow vertically into the cargo area of a truck – e.g. used in city centers – and hydraulic controls over the chute's orientation and deflector enable a precise placement of the removed snow. Snowblowers are therefore crucial when accurate placement of the removed snow is necessary or when there is no option to store it next to the driving path (e.g. in driveways).

(a) Two-stage snowblower

(b) V-shaped snowblower

Figure 2: Two different principles of snowblowers

Sandspreaders are needed when winter conditions cause slippery roads and walkways. Winter road sand or salt are spread to increase the grip on the surface or to melt ice. The machines are either carried like a bucket or dragged as a trailer, use different spreading mechanisms (drum or disc spreading). While the working width of drum spreaders equals approximately their physical width, disc spreaders can spread up to ten meters wide and off-center using the centrifugal principle (see figure 3) which gives them a wide application range. Spreaders can be self-loading or require a second vehicle for loading and solutions for automatic, driving-speed dependent spreading adjustment are the current product innovations.

(a) Rear-mounted disc spreader

(b) Dragged drum spreader

Figure 3: Two different principles of spreaders

Sweepers are a product range useful not only during winter season. They can be used to remove light snow more effectively than plows or blowers in winter but also for general cleaning of roads or similar surfaces during all other seasons. Sweepers are especially useful in spring season, when the snow has melted and residues of sand-spreading remain. Water tanks to reduce dust while sweeping can be attached to the machines and different lengths and diameters of the brushes provide the right sweeper for any scenario.

Figure 4: Sweeper

From these four product families that again contain products of different sizes and in other variations one can identify the large product mix that Tokvam is offering to date. Demand of the products changes according to seasonal conditions; while a snow-heavy winter causes customers to buy more snowblowers and snowplows (and to stock up on specific spare parts), a rather icy winter is likely to increase the sales of sand-spreaders which again causes a higher need for sweepers in the following season. Together with the increased customer demand of variety in the product range this adds to a challenging and changing environment that the company operates in and has to cope with.

Specifically with regards to the welding system, one can see the manifold of steel components in various shapes and dimensions that Tokvam products consist of. Bent and laser-cut sheet metal parts that range from very small parts to large chassis components as well as steel profiles in different lengths and shapes all need to be handled by the same manufacturing system.

4.3 The manufacturing system

The production is separated in two buildings (see the schematic layout of the factory (not to scale) in figure 5): The first one contains the warehouse for steel plates and profiles (L) together with the welding department (A-F) and administration (K). The paint shop (G-I) and assembly (J) together with the warehouse for semi-finished goods are located in the second building. Finished goods are stored on the company's yard before shipping. The welding department consists of two robot welding cells, equipped with Kuka (KR16L6ARC (F) and KR 30L16 (E)) robots, and manual welding stations (A-D) for either tack welding as preparation for the robots or for complete welding of certain parts. Downstream the process the welded parts are transported to building two for shot blasting (G), painting (H) and drying (I) on one common conveyor. Afterwards they are stored as semi-finished goods or transported straight to the manual assembly line (J) where all machines get assembled and prepared for shipping.

The employed system is flexible enough to cope with the demand of the high variation in the product mix since welding is currently the only partly automated process. Since manual welding prevails for a large number of – especially small – parts, the manufacturing system is in fact highly flexible but lacking utilization of the available robotic welding systems. Keeping this high level of flexibility is required for being able to adjust the production plan according to long- and short-term changes in the future. At the same time, a higher utilization of the available robotic welding systems or in general higher productivity through automation is necessary in order to reduce the cost of manufacturing.

4.3.1 The two welding robots

The two Kuka KR16L6 and KR30L16 robots are equipped for arc-welding and located side by side, at one end of the factory building containing the company's welding department. While the larger one (KR30L16) has a maximum reach of ca. 3 m and rated payload of 16 kg, the smaller one (KR16L6) has a maximum reach of ca. 2 m and a rated payload of 6 kg. Both robots run usually only during operating hours, which means maximum two shifts per day.

The large robot (E in figure 5) mainly produces chassis for all types of machines and large parts like intake-augers, three-point hitches and snowplow wings. Its welding cell features a horizontal positioner which is capable of turning even the heaviest parts (e.g. chassis for large drum spreaders as seen in figure 3b) so that the robot can reach all positions with the welding gun. It produced 38 different parts and had a total output of 1193 parts in 2018.

The small robot (F in figure 5) produces small parts, e.g. feeding vanes for v-shaped snowblowers, suspension parts for snowplows and different kinds of covers and spare parts. These can be typically welded in an array of three or more during the same cycle (before the human operator has to take out the finished parts and set in new components again), while – due to the size – the

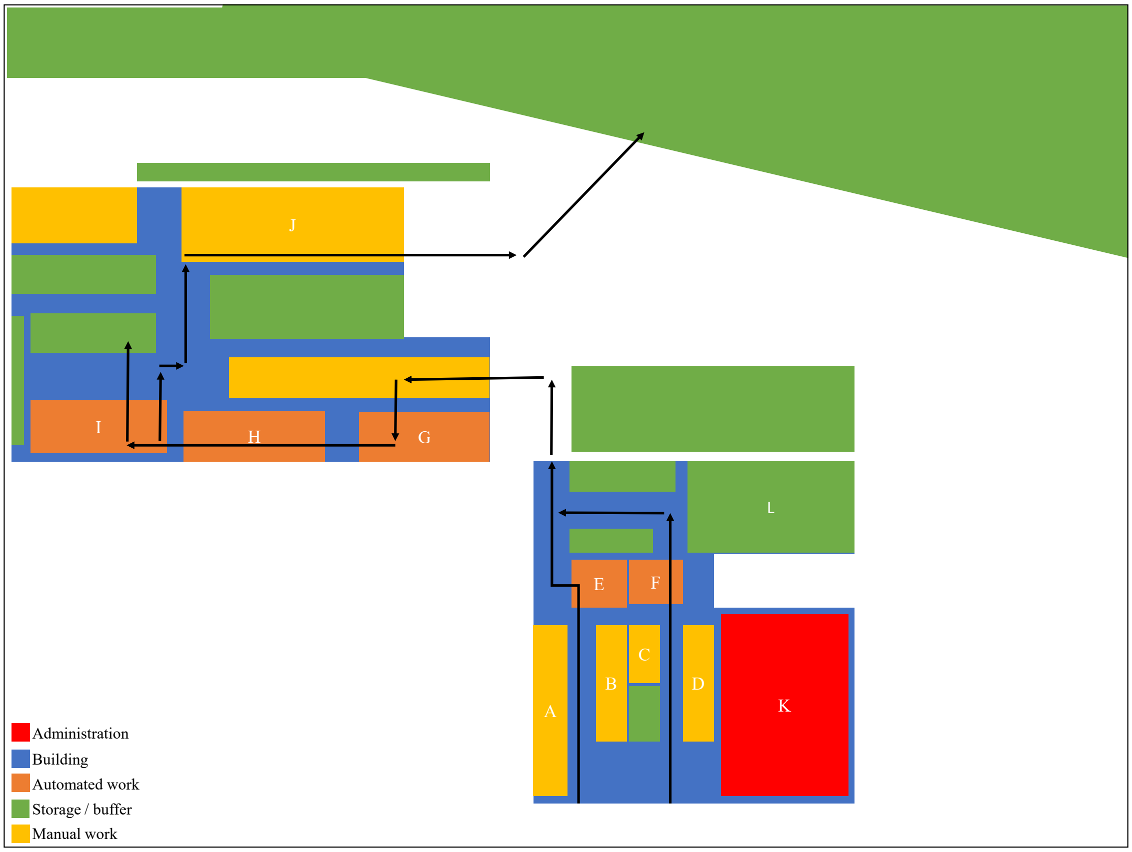


Figure 5: Schematic layout of the factory (not to scale)

large robot typically only welds one part per cycle. In 2018, 40 different products were produced on the small robot with a total output of 3248 parts. Comparing this output with the one of the large robot, the variety of parts welded in the small robot is just as large (ca. 40 different parts) and the total output is a little bit less than three times as much. Both robots have theoretically the same available production time and the small one welds usually three or more parts per cycle. Still, due to the way smaller parts the small robot should be able to produce a much higher output compared to the large one which is running constantly. This leads back to the problem statement as introduced in section 1.1.

The large robot is not of concern for this thesis, therefore whenever a robotic welding system is mentioned in the rest of this work, it concerns the small robot as described in the paragraph above.

4.4 The current robot welding system

Currently, the robot welding system – as can be seen in figure 6 (not to scale) – consists of the robot welding cell together with manual workstations for preparation of the robotic process. The welding cell is separated into three sections, each section can be reached by the Kuka KR16L6 welding robot which can be moved on two rails. The robot has to be moved manually on the rails and has to be fixed to a position before the welding process can start, thus the rails do not provide an additional axle for the welding process but only means to move the robot between sections of the cell. Two sections feature a horizontal positioner to turn parts. The third section contains a bisected rotating board which allows for placing parts on the half facing the outside the welding cell while welding continues on the half inside the cell (the bisection of the board is provided by a steel-screen for safety). This rotating board does not feature a positioner, which means that the parts welded on the board remain in fixed position during the welding process.

Since all three sections are part of one common cell, it is not possible to work in any section while robotic welding is in process due to safety hazards. Light barriers and sensors to ensure that all gates are closed stop the robot if a worker accesses the cell or turns the board. The robot cannot move on the rails automatically, thus it is restricted to work on only one section at a time.

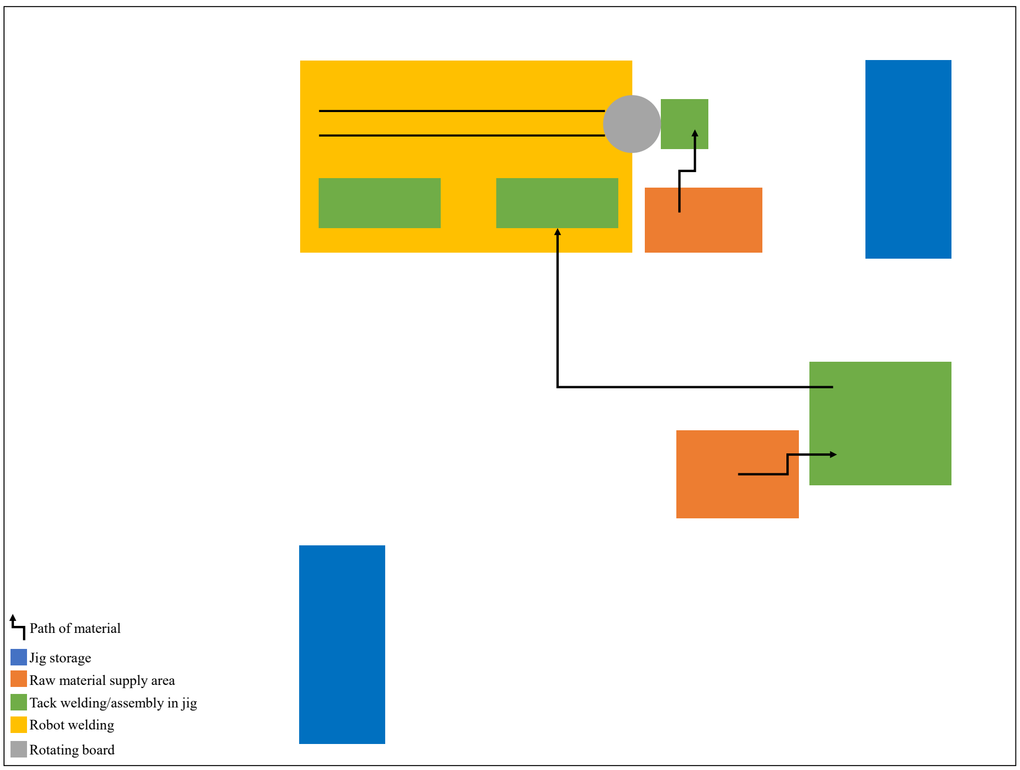


Figure 6: Schematic layout of the current robot welding system (not to scale)

The manual work in this welding system consists of preparation of the components. This means assembling components in robot-welding jigs and tack welding them together. Robot-welding jigs are jigs that can be mounted on the rotating board or positioners, which hold the pieces in place during the welding process. They are designed to hold the pieces in place and prevent warping (which is a side effect due to the induced heat of the welding process). During the observation of the welding robot, the author found that the current system of handling and storing jigs in different storage locations (blue areas in figure 6) can be another weakness of the current state. Some robot jigs are stored in vicinity of the welding cell, others in the warehouse behind ((F) in figure 5). See therefore the designated section 4.5 about jigs. Tack-welding happens either with help of using already the robot-welding jig, a manual welding jig or no jig at all (relying on measurements and clamps in the latter case). The welder fixes the parts together with a few weld points, which cannot bear large mechanical forces. They are only meant to hold the parts in place for the final welding, performed by the robot in this system. To support manual tack welding, jigs can be used. This saves time by reducing the need to measure in order to set parts in the right orientation. It assists the welder, especially when handling more than two parts at the same time. The jigs are stored close to the robotic welding cell, some of them have to be handled with a crane while others (especially the manual welding jigs) are smaller and lighter and can be handled manually.

Figure 7 shows the process flow of a typical welding process. The operator starts the welding job in the company's ERP system and orders the components to be delivered to the manual workplace. If the welder knows that jigs are available for the parts and where to find them, those need to be found and delivered to the workplace as well. The welder pre-assembles the components (using a manual tack-welding or robot-jig if possible), places them with the robot-jig in the welding cell and starts the welding program. Some parts can require to be manipulated manually during the welding program while others can be finished in one cycle. Especially on the rotating board, where the parts are not accessible for the robot from below (due to the board), a manual operation during the welding cycle can be necessary. In this case, the operator turns the table and flips the components on the outside while the robot welds on the inside. The robot can then - in the next step - weld the opposite side of the just flipped components.

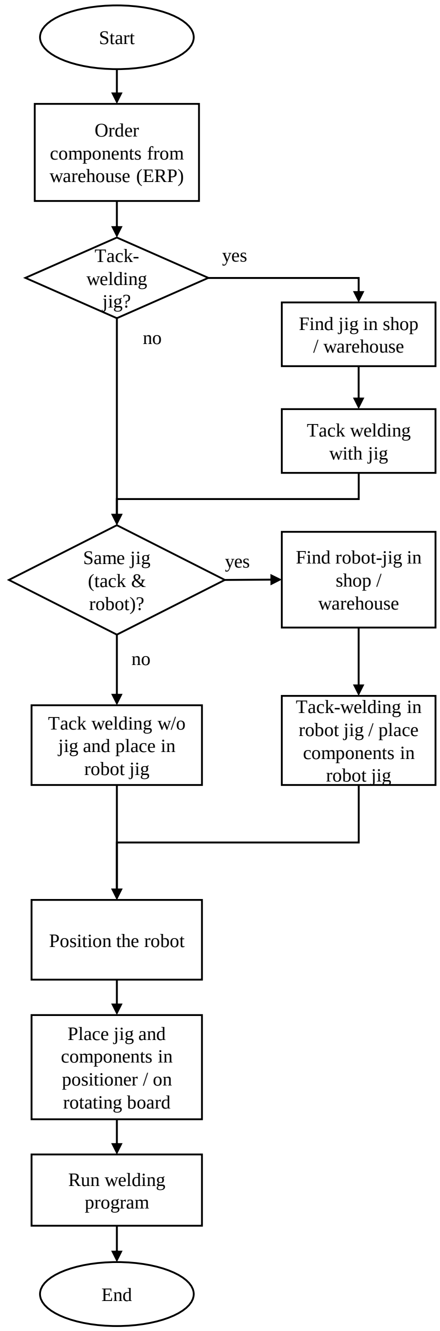


Figure 7: Current robot welding process for one welding cycle

4.5 Jigs in the current system

In the current state, jigs are not thoroughly integrated into the company's ERP system. This has various consequences which all lead to one large problem: it is hard to plan with jigs in any process. The two main types of jigs are described in the following sections, along with the difficulties that arise in the current system.

While workers know about the existence of specific robot jigs, finding them physically is challenging. The more important problem of robot jigs is, that changes in the products design (e.g. dimensional changes) may or may not be adjusted in the jig design. There is no connection between the revision number of the product and the jig. Manual jigs on the other hand can be rather seen as a help to assist production, thus it is possible to produce without them (with a negative impact on productivity) and the existence of a jig cannot be taken for granted. Therefore, either a worker knows about the existence or not which makes the decision points in the current robot welding process (see figure 7) challenging. There is no systemic integration of the jigs in the manufacturing processes which tells workers when there is a jig and when there is not. The challenge with finding the physical jig comes in addition, as well as the problem of linking changes of product design with jig design.

4.5.1 Robot jigs

The reason for using a jig can be its bare necessity for fixing components together for being handled in the manipulator of a welding cell. This type was previously referred to as a robot welding jig or robot jig. In that case, the robot welding process simply cannot be executed without the jig and usually those jigs are rather large in size. This means that if there is a welding program for a product, there is most likely a robot jig as well. The time used for finding the location where the jig is stored depends on experience, by default most robot jigs should be stored close to the robotic welding cell (see blue boxes in figure 6) but they might also be found somewhere else. Some robot jigs are marked with the name or article number of the product that they are used for, others are not. If the shape of a product or single component changes due to redesign, usage of standard-components or other reasons, the jig might have to be changed as well. These changes can reach from minor geometrical adjustments to more comprehensive adjustments or even require rebuilding the whole jig. The larger (or more obvious) the change, the more likely it is that a change in the jig-design is noticed by the workers in the welding department. If a component does not fit in the jig anymore at all, it is obvious that the component got revised and the jig needs to be changed accordingly before the product can be welded. Minor design changes on the other hand are less likely to be noticed and happen more often than major redesigns. If it is only a dimension or angle that needs to be adjusted to make the jig fit the revised product, everything might fit in the jig just as usual. In the worst case, the incorrectly welded parts continue their way through shot blasting and painting and the failure will not be noticed until they do not fit the final product in assembly. These failures are currently being prevented by the bare experience and knowledge of the employees in the factory, the short and easy means of communication and the flexibility given through the extensive amount of manual work on the shop-floor. These means to prevent failure work in the system by the state of today but as soon as factors change this will not be viable anymore. Changing factors can be new employees with less experience, longer communication lines when the company and number of employees grows/changes towards more administrative employees and a less flexible, less human centered production system with an increased amount of automated processes.

4.5.2 Manual jigs

The previously described challenges of the current handling of jigs were focused on robot welding jigs. As mentioned before, jigs are also used for manual welding and tack welding, as well as in the assembly line. What sets these production processes apart from robotic welding – when talking about jigs – is the fact that none of them relies on using jigs entirely. Any of these processes can – theoretically – be carried out without a jig. Practically this is not viable due to the loss of quality and time that would go along with not using a jig. The problem that arises from that fact was touched upon in the beginning of this section: if an employee does not know that there is a jig available for the process, the piece might just be welded without using one. This is not problematic in terms of accuracy as long as the worker follows the drawings and e.g. measures against warping are taken (which can be assumed since the welders are professionals in their field). Yet, the extra time needed for measuring and arranging the components will increase the cost of producing the part dramatically, not to mention the delay in the downstream processes and the disruption of the overall production plan. The reason why especially the workers in the welding department are currently well informed about what jigs are available, is because they are the ones making most of them. Most of the manual and robot jigs are produced and maintained in house and consist of simple sheet metal and tube constructions. This gives the welders the freedom to make exactly the kind of jigs they need and adjust parameters if necessary. The problem here is, that this is not backed by any system. While jigs for the assembly department are usually requested through production engineering and developed by the responsible product engineer (which means that at least the responsible departments are informed), the freedom in the welding department prevents this flow of information. Thus, a product engineer will most likely not consider an existing welding jig when redesigning a welded part. Or a newly employed welder will have no way to work on production orders independently from experienced workers.

5 Proposals for improvement of the current state

The current state of the robotic welding system – with its challenges described in the chapter above – is not optimal. The following chapter will present the proposed options for improving the current state.

Section 5.1 will show two solutions of replacing the robotic welding cell with a new welding system. Two different systems will be proposed. Section 5.2 will present what needs to be done with the jig system in order to optimize the robotic welding process with the current robotic welding cell. Section 5.3 will present the option of adding another robotic welding system to the already existing one, using a hybrid robotic/human workstation.

5.1 Offers for alternative robot welding systems

In search for a better solution for the welding department than the robot in use, Tokvam contacted suppliers within the robotics and automation industry to propose a robotic welding system suiting the needs of the company. The two offered solutions by independent suppliers S1 and S2 will be described in the following section.

5.1.1 Offer by supplier S1

The company S1 is specialized on solutions for robotized low batch production and offers a system using ABB robots. The offer comprises a 6 degrees of freedom (DOF) ABB welding robot, a 3-axis robot-controlled positioner and an automated pallet handling system to store and transport welding jigs, components prepared for welding (tacked together) and finished welded parts between the welding cell and a storage rack. A model of this system – as proposed for Tokvam – can be seen in figure 8. While the figure shows one manual workplace, more manual workplaces are also possible to realize with this system since the the tack-welded components can be buffered in the rack up to a certain extent. Welders can assemble the components in jigs, supplied by the pallet handler from the rack. When a pallet is ready for welding, the pallet handler can – depending on the welding cell's status – transport it to the welding cell or buffer it in the rack. After welding, the finished part can be buffered in the rack or transported for further processing. Depending on the processing time inside the welding cell, more manual workplaces can suit the production system better than only one (see checkered pattern in the right part of figure 8). The constraint for the maximal amount of places is the available space, the system could be extended with another welding cell as well if that was necessary (and possible with regards to space) in the future.

A similar setup is installed at at the Swedish reference company RC, a manufacturer of agricultural equipment but producing in a larger scale than Tokvam. The system differs from the one which was proposed for Tokvam both in size and in its layout. Two robot welding cells are implemented, each including two ABB welding robots on a gantry and one positioner. The pallet handler

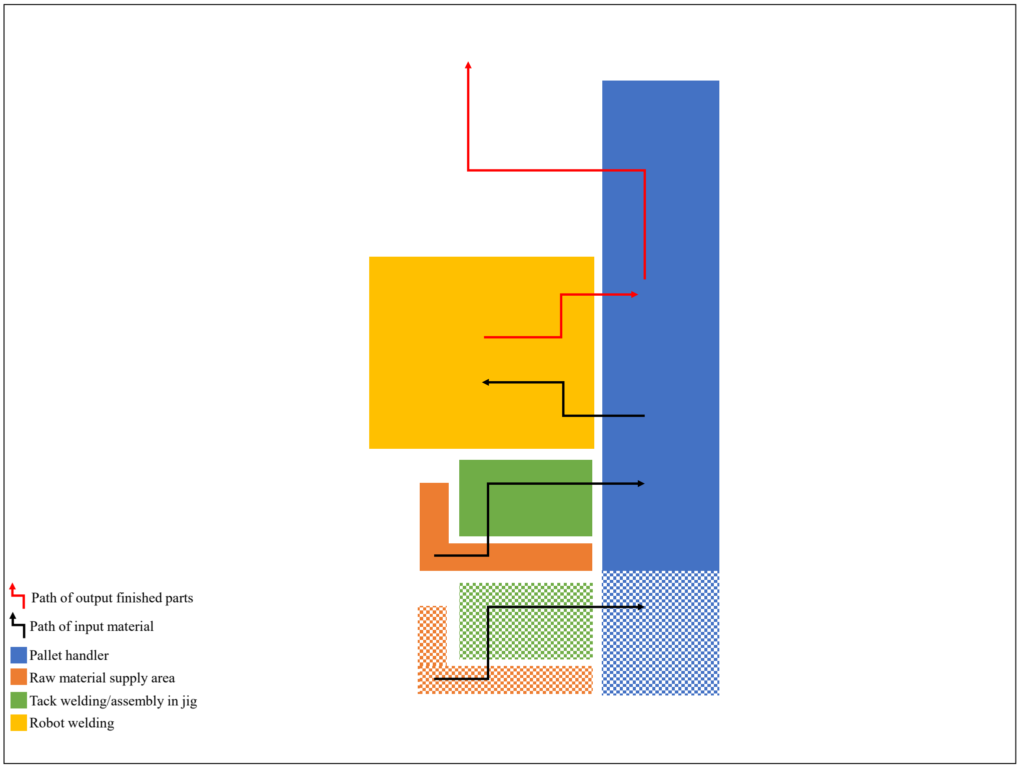


Figure 8: Schematic layout of a possible S1 system for Tokvam (not to scale)

is loaded from the right and acts as a buffer before the welding cells. The single parts are tack welded and assembled in jigs in the manual workplaces to the right, which are supplied with raw material from the right. A logical flow of input material is achieved from the right to the left of this system, following the black arrows in figure 9. The finished parts exit the system through the pallet handler. Components are supplied in direct relation to the produced parts, which means one container contains all necessary sheet metal parts for a single product. Steel profiles – due to the length – are supplied in an additional long container, again one container per produced product. Using that system it can be prevented that parts on the final welded product are missing. A drawback from that system, as mentioned by the workers on the shopfloor, is that components are not always in the same order and might be covered by heavy or larger parts in the container. To cope with that problem and gain more control over how especially the laser-cut sheet metal parts are packed and delivered, RC is expanding for insourcing the production of laser-cut sheet metal parts.

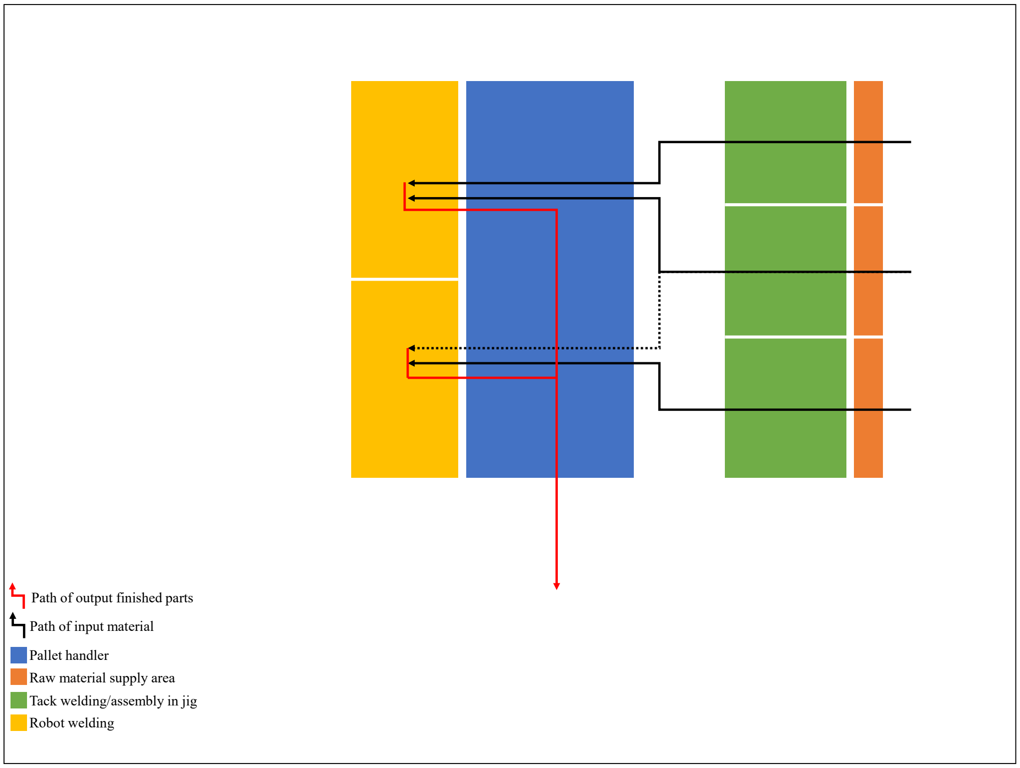


Figure 9: Schematic layout of S1 system at RC (not to scale)

5.1.2 Offer by supplier: S2

S2 is a supplier of Yaskawa robot systems and located in Norway. The suggested robot welding system includes two Yaskawa robots, one for handling payloads of up to 500 kg and a smaller welding robot. In comparison to the offer by S1, this system does not feature a storage solution for jigs and parts and reflects thus a lower level of automation. It is set up in a circular manner with three gates for manual preparation of parts as can be seen in figure 10. The parts need to be either tack-welded or assembled in fixtures using e.g. clamps and fixed in frames which the handling robot can grasp. The handling robot then picks a frame from one of the gates and manipulates its orientation for the welding robot to weld in optimal orientation during the welding process. During that time the three gates can be used to prepare the next part and to buffer the previously welded one for further processing (transport to the next operation).

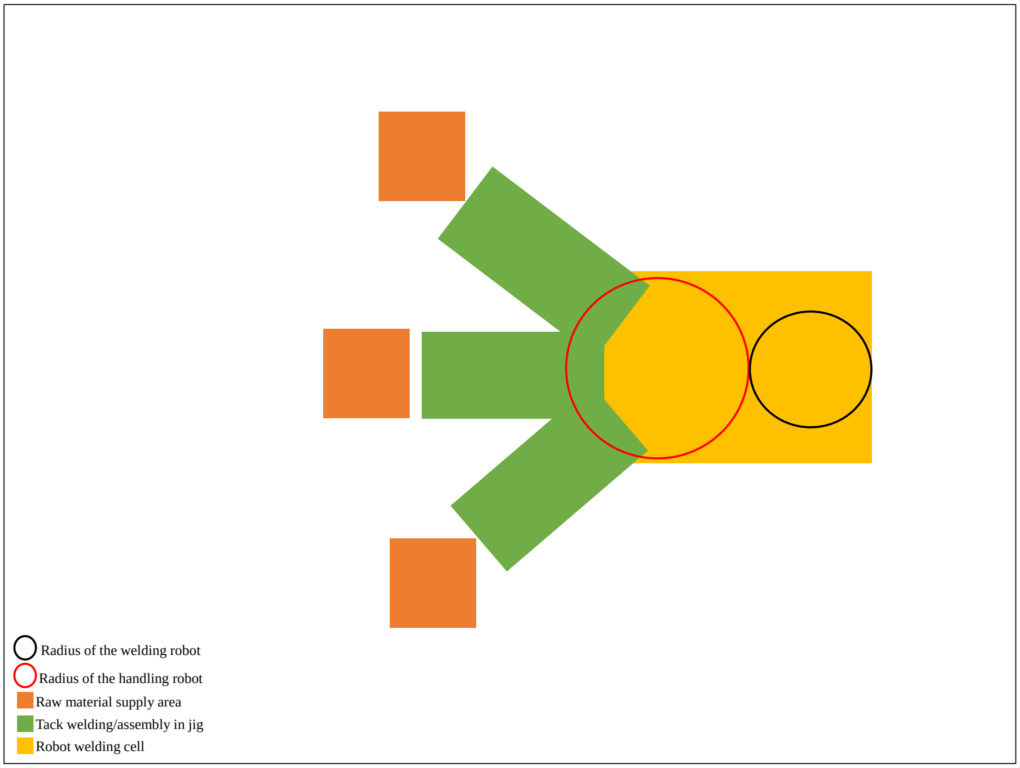


Figure 10: Schematic layout as proposed by S2 for Tokvam (not to scale)

5.2 Improvement of the jig system

Jigs are currently not thoroughly integrated into the company's ERP system. While a free-text search for item names which contain the word "jig" has ca. 500 results, about 200 of those items are jigs made in-house (as opposed to ca. 300 bought components to produce them). The majority of these self-made items are actual jigs for manual or robotic welding or assembly. From these 200 jigs, 50 were first introduced in the last two years and about another 50 since 2015. The oldest registered jig is from 2013 (two years after the introduction of the current ERP system). All jigs which can be found in the ERP system are assigned to a hypothetical storage location "99", which is not connected to a physical storage location.

Besides these 200 items which are registered in the ERP system there is an uncountable amount of self-made, unregistered jigs which are mainly found in the manual welding department. Here, the employees have the freedom, tools and material to develop and make their own tools and jigs, bypassing the engineering and planning department and the ERP system. This means, whenever a welder encounters a job which causes ergonomic issues, is time-consuming or can in other ways be improved by a jig, the employee can just make that jig (provided the skills and time). This is an excellent example of preventing waste by not using employee creativity as described in lean-theory

Liker & Meier (2006). Tokvam manages to use the creativity and skills of the employees by engaging them in finding solutions themselves. Unfortunately, there is no system in place to integrate these jigs into the rest of the company which in the worst case means that – except from the welder who made the jig – nobody will ever know of its existence. As described in section 4.5, this can cause a string of negative events when thinking of component-revision numbers and prevents any other welder from knowing about and where to find the jig.

The proposal aims to integrate all these jigs that are physically available into the ERP system by assigning them unique item numbers. During the same initiative, the ones that will not be used any longer shall get scrapped and it needs to be ensured that the ones which are kept are in a useful condition and match the respective product's revision number (in terms of geometry). The jigs need to be integrated in the company's existing warehouse-logic, which is in use for most other items but jigs, so that any employee can locate the physical jig by searching it through the ERP system and using a warehouse map. A function in the ERP system which is not in place yet needs to be established in collaboration with the system's integrator. This function shall serve to connect a jig's item number to the respective product's item number. When starting on a work order for a product, the employee must receive an information about which jig to use and where to find it. This can further be connected to a tool check-out system to ensure that the jig is delivered back to its storage location after the job is done. Ultimately, setting up a company standard for how to treat jigs in general is necessary to sustain these improvements. This standard must not antagonize the current freedom to develop and produce jigs in the way that it exists today. It must rather improve the collaboration between the involved parties and set a standard for who is responsible for which part of the jig-development process and who needs to be informed when a new jig is made (and vice versa, when a product changes and a jig needs to be adjusted). The changes proposed above apply both to currently unofficial jigs as well as to those which are already integrated into the ERP system.

A tool which can be used to achieve this systematic organization of jigs as described above can be the 5S-method. This is a method, common in lean projects, to eliminate waste and ensure constant improvement using the five-step circle: sort, straighten, shine, standardize, sustain (Liker & Meier 2006). These five steps in relation to what has been proposed above relate as follows:

Sort: Scrap broken jigs and jigs for discontinued products.

Straighten: Systematically integrate all jigs in the ERP-system, give them unique identifiers, storage locations and connect them logically to the products that they shall be used for.

Shine: Clean the jigs, in this regard especially ensure that the jigs' geometry matches the product's current revision number.

Standardize: Set up a standard to ensure all actors in the process of designing, making and using jigs know their responsibilities. Make sure that the standard does not override today's flexibility but rather supports the process (e.g. by officially allocating the time for the construction of jigs in the welding department).

Sustain: Ensure that the organization keeps learning and follows up on the new system, not only fixing the problems with existing jigs but also ensuring those benefits for new jigs/other jigs (for example streamlining the process of applying for jigs in the assembly department).

5.3 An additional hybrid welding station

Before starting on this section, the author wants to clarify the meaning of *hybrid* in this case. The hybrid welding station is a system equipped with a welding robot which can as well be used as a workplace for a human welder. This means that the system needs to be equipped with a strong fume-extraction hood and bright illumination for a welder to work there under the best possible conditions. The workplace is supposed to have no drawbacks in comparison to the other manual welding workplaces at Tokvam, it shall rather serve as a benchmark for how to equip future manual welding spaces. At the same time it will be equipped with a robotic welding system to easily automate welding jobs. The *hybrid* solution in this case is not meant to be a workplace where the robot and a manual welder shall manufacture parts at the same time. Rather they shall collaborate in the teaching phase and during the robots welding operation, where the welder can be present in the cell without safety hazards. The author wants to emphasize that this system is also supposed to serve as a learning platform for how to integrate human and robotic work by the example of welding for Tokvam. Future projects can build upon this basis to further develop human-robot collaboration (HRC) in the company.

The supplier S3 offers a robot welding system called "EasyAutoWelder" which includes a 6 DOF robot arm from Universal Robots, mounted to a welding table (sizes ranging between 1200x800 and 2000x2000 mm). The end-effector is equipped with a welding gun mounted to a system developed by S3 called "Teachgrip". In combination with a touch screen, this grip acts as what is known as a teach pendant on traditional welding robots.

The effective operation of a robot welding system is not only determined by the welding process alone. What stands out to be a highly influential factor – especially in small businesses – is the programming of the robot system (Pan et al. 2012). In principle there are two ways of programming a welding robot: on-line and off-line. While on-line programming means teaching all the necessary geometries, movements and parameters to the robot using a teaching pendant on site right next to it, off-line programming generates the required programs straight from available computer aided design (CAD) data on a PC. The latter does not have to happen in physical vicinity to the actual robot, it does not interrupt the robots operation and parameters in a welded part can be easily adjusted without having to recreate the entire welding program. On-line programming on the other hand cannot be performed while the robot is in operation, the programmer has to guide the robot through the movements of the program manually and record them, which together with other parameters creates the welding program afterwards. When the design of a welded part changes, its welding program usually needs to be rewritten entirely if it was created using on-line programming. Reference points that were recorded using the original design of a part may have a different location in a revised design, thus the following sequences of welding operations are no longer accurate. While the benefits of off-line programming were highlighted in the previous paragraph, it is necessary to note that for SME's this is usually not a viable option, due to the complexity of an off-line programming system and the costs that go along with implementing and maintaining it (Pan et al. 2012).

One approach to on-line programming that goes beyond the use of a teach-pendant is teaching by demonstration where the robot can be moved freely by hand instead of being jogged by a teach pendant (Onda 2001). This method uses force- and torque-sensors at the robot arm's end effector to track the operator's directional commands when moving e.g. the welding gun to a specific point, so that the robot can follow the operator's movements. Thus, the operator can move the welding gun to all positions on the work-piece by hand and save those in the welding program, connecting them by a standard set of trajectories. Pan et al. (2012) mention this method as it was already proposed in its principle in 2006, the robotic welding system by S3 uses just this principle for its "Teachgrip".

Du et al. (2018) mention the importance of natural interaction for collaboration between robot and human and present a solution for motion tracking and speech recognition to teach a robot. Even though this form differs from the "Teachgrip", it serves the same purpose: to reduce the need for robot-programming experts for fast and efficient programming of robots. While traditional teaching modes are not only slower and therefore less cost effective, the complexity of the teaching programs hinder them being used by non-experts in robot programming, which might be just the company's expert that is rather skilled in welding than robot programming.

The "Teachgrip" principle requires less understanding of the coordinate system that the robot is operating in, the logic of the robot's movements and is connected to less learning effort than learning how to move the robot using a teach-pendant. This more intuitive method can allow the process of teaching to become less dependent on experts in robot programming. This opens up the process of on-line programming for experts in the manufacturing technique that the robot is meant to replace, which means that more expert knowledge and experience can be incorporated in the programs. While this method is adopted by other robot manufacturers and suppliers than S3 as well, it still prevents the robot from running while teaching is in progress. Its improvement potential does not lie in eliminating the unproductive, occupied time of on-line programming. Still, the more intuitive way of controlling the robot arm provides for shorter programming times. Further, teaching the robot does not become dependent on the availability of the few experts in robot programming anymore. Teaching jobs are less likely to be come delayed if more people in the company are able to do the job, thus more products can be welded automatically.

The author sees an opportunity of investing in not only a hybrid welding cell which can provide for both, more workspaces for manual welding and a higher level of automation in the welding department. But also, in a stepping stone for the company to use innovative technology in HRC together with Tokvam's most valuable asset, the skilled and creative workers.

Where robotic welding and human operators were previously separated from each other by safety fences, in the HRC-enabled system the welder can seamlessly interact with the parts on the robot's welding table. This can be used for e.g. placing or tack welding components for the robot, while the robot is welding another part at the same time, one step further in the process. Müller et al. (2017) present this as the cooperation method, where the operator works in the same workspace as the robot but on a different task. Safety devices to adjust the robot's motion for the sake of the worker's safety like safety shut-off mats can enable the robot to identify when a human is present in the workspace, to adjust certain parameters.

When considering the integration of HRC throughout more processes than just welding, or in other forms for the welding process (e.g. handling-robots), one can find many possibilities to use collaborative robots to augment the manual work as well. This offers research opportunities at Tokvam, for future collaboration with e.g. NTNU.

Due to the small footprint and the self-contained system (the robot with all its equipment including welding power-source), adding additional EasyAutoWelder-systems requires relatively little effort. This adds the option of scalability to the solution, if the implementation of one system proves to be a successful addition to the current manufacturing system. This improves the production system's ability to cope with rising demands, as described by Hu et al. (2011).

6 Discussion

In the previous chapter, the main solutions have been presented to tackle the problem with the under-utilized robotic welding cell and increase the ability of the company to cope with the demand of a large product variety while maintaining short delivery time and quality products. While all presented solutions should provide an improvement of the current system of some kind, their impacts and risks are different and need therefore to be discussed against each other.

6.1 Investing in new robot welding system to replace the current system

Two solutions aim on completely replacing the current robotic welding system as it is shown in figure 6. Those are the solutions offered by S1 and S2. The two systems will be discussed separately in the following subsections,

6.1.1 Replacing the current robot welding system with the S1 offer

As the offer comprises a complete system, including the storage solution for jigs, this solution is perceived as the most comprehensive one for replacing the current robot welding system. For this to work as experienced at the reference company RC, a substantial part of Tokvam's welding system needs to be restructured. Physical changes of the manufacturing plant are inevitable, which include amongst others raising the welding-hall's roof to provide space for the storage rack.

The systemic change includes a change in the handling of welding jigs, similar to as what is proposed as a separate solution but specifically designed by S1 to suit the welding system they provide. This is necessary due to the currently not-systematic handling of jigs, yet it prevents introducing a tailor made solution that fits the overall production system of Tokvam (including welding, painting and assembly), since it would be designed specifically to suit the welding system as proposed by S1. This can be seen as both a challenge and an opportunity: making a new solution for jig-handling a requirement for the new welding system integrates these two solutions and thus offers improvement opportunities in both processes. At the same time, the risk that a new and foreign-developed jig-handling solution exceeds the company's capabilities and that the project fails is rather high. If Tokvam can develop a solution in house which is understood and supported by the employees and takes the individual aspects of Tokvam into consideration, the chance for this system to work on the long term is much more likely.

The welding robots in this scenario are from ABB, since employees are mainly used to Kuka robots this means that learning to handle the new programming systems is necessary. Since all the other offers do not contain Kuka robots either, this is not a problem unique to the solution of replacing the current robot welding cell with the one proposed by S1, still it needs to be mentioned.

What sets this solution apart from the one by S2, is that the robot welding system in itself can be considered a systematic solution which is planned by the supplier to be self contained. Its interaction with the other parts of Tokvam's production system can be questioned but the interaction of the welding robot, the manipulator, the pallet handler and the storage unit is proven to be reliable since these combinations are already operating successfully elsewhere.

Another unique feature of this solution is its ability to operate unmanned, if enough buffer is built up before the welding robot before an unmanned period (i.e. the night shift). Before

6.1.2 Replacing the current robot welding system with the S2 offer

Compared to the offer from S1, the one by S2 does not feature a system for storing and supplying jigs to the robot welding system. This means, that the robot welding cell with its Yaskawa welding and handling robot can theoretically be operated within the current production system without implementing a systematic solution for the logistics of jigs. While the currently used jigs still need to be adapted to fit the mechanisms used in the proposed robot welding system, an organized storage and logistics solution does not need to be invented. It is – nevertheless – crucial to provide for having the right jig at the right workplace at the right time in order for the proposed system to work effectively.

Continuing to use the current practice of searching for the right jig and relying solely on the internal competence of the employees to know if one is available, where it is stored and how it is used would soon become a bottleneck in this new robot welding system as well.

The absence of a jig-system in this offer gives two opportunities: first, to implement the robot welding system without any change to the handling of jigs, and second to implement a jig system, individually designed for the case of Tokvam, before implementing the new robot welding system and having the integration of both in mind. While the improvement opportunities with the first option are limited, the second one has the potential to solve the most problems from the current state. Again, the system offered by S2 does not use Kuka robots but Yaskawa instead, which means additional expenses for teaching employees about using the different programming environment than the one they are used to.

6.2 Systematical reorganization of jigs

As can be seen from the previous section, a systematic way of organizing jigs is crucial no matter which solution is chosen. As a stand-alone solution, the impact of an ERP supported system to organize jigs at Tokvam already yields benefits for multiple departments and processes without being connected to a large economical investment, especially in comparison to the proposals of replacing the robot welding system with a new one. The company just recently updated the ERP system to its newest Version and a list of requirements to the system's vendor is constantly being updated. This means, the financial effort to program a solution as described in section 5.2 needs to be evaluated by the project group prioritizing the future ERP implementations. The remaining work of this reorganization project can be carried out in style of a 5S-workshop, where the first three phases (sort, straighten and shine) can be concentrated work for a task force and standardization and sustaining of the changes and improvements can be carried out according to the company's quality-management system.

6.3 Adding a hybrid welding station to the welding system

The by far cheapest solution (in comparison to the other two implementations of new robot welding systems) is adding one "EasyAutoWelder" as proposed by S3. The price for investing in this system and to implement state of the art technology in Tokvam's manufacturing system is approximately ten times cheaper than the solution proposed by S1.

Due to the self-contained system which is mainly mounted to the welding table, no physical structural changes to the company's building are necessary that would not be made otherwise anyway (e.g. adding another fume-extraction hood to the ventilation system). This has also an advantage if the company found out that the hybrid system does not fit to the needs of Tokvam after all. In the worst case, the system can be sold again, the customer range for such a universal welding system is wider than the one of a custom solution as proposed by S1 or S2.

If on the other hand the system fits the requirements just as expected and is fully utilized by the welding department, adding another module requires just as little effort. Fur future growing demand, this solution is scalable whereas the proposal by S2 is not planned to be. The proposal by S1 can be extended by adding manual workstations but it does not include an easy way to increase its robot welding capacity.

What sets the hybrid welding station apart from the other proposals, is the opportunity for trying a new approach to robotic welding with the integration of the welders into the teaching process by HRC. Making the teaching process more accessible to welders with less experience with robot programming increases the amount of people in the company who are capable to teach the robot and transfers the technical welding know-how from the manual process into the automated one (Müller et al. 2017). Engineers gain the possibility to test and teach new product designs independently. This raises the overall skill level of robot programming and at the same time enables knowledge from new disciplines to influence the quality and efficiency of robotic welding. As further argued by Müller et al. (2017), for a small enterprise like Tokvam, a fully automated welding system can simply become an overwhelming challenge. The high variability in products and thus, required flexibility are far more important to the company's success and the lack of experience with highly automated systems prevents its ability to utilize this feature effectively. Effective automation which enables the employees' experience with the manual process to be transferred into automating a few processes can be more beneficial than focusing on efficient automation to increase the output of produced parts (Müller et al. 2017).

6.4 Suggested solution

The author presented the different robot welding systems which can replace the current robot welding system in chapter 5 and discussed the risks and opportunities in which they differ in the previous sections. The unsystematic handling of jigs in the current state of the system was identified to be a big contributor to the troubles that Tokvam is facing in the current robotic welding system, how to address this issue was proposed in section 5.2 and put in context with the other proposals in the previous discussion. As an alternative to replacing the current robot welding cell, adding a hybrid welding station was found to be a possible solution to increase the number of automatically welded parts at Tokvam. This solution is further connected to side effects which go beyond improving the manufacturing system's performance. It can act as a stepping stone for the company for implementing creative solutions which combine the experience and skills of the employees with robotic augmentation, creating an environment for HRC and opening up for future collaborations with partners like NTNU and SINTEF to research in this field.

As the hybrid welding station is also connected to the least financial risk in comparison to the offers by S1 and S2, the author proposes to invest in such a system to solve the problems of the current state and prepare for future challenges. At the same time, it is necessary to set up a system for the handling of jigs in the company due to its impact on the current welding systems, the future system and other departments of Tokvam. In combination, these two proposals promise a sustainable advantage for the manufacturing system.

7 Conclusion

In this master thesis, a robot welding cell was analyzed from a system's perspective, in context with its environment and other systems in this environment that affect the welding cell's productivity. This welding cell was initially meant to be replaced and this thesis was supposed to serve as a decision tool for choosing the best possible replacement.

Tokvam has a broad product spectrum with a large variety of components, in order to always provide the product which the customers require. This requires a certain flexibility in manufacturing, allowing for production orders to adapt to what the market demands, and the ability to adjust production volume depending on seasonal changes. At the same time, to provide for quality and a low production price, a high level of automation is desired.

During the process of observing the company's welding system, where the author spent an extensive amount of time on site talking to employees and analyzing the robotic welding process, it became apparent that extending the magnifying level could reveal other subsystems of the manufacturing system that need to be considered as well. One of these subsystems is the way how (welding) jigs are managed currently, which affects the robot welding system substantially.

Another component that is crucial for Tokvam's success are the employees in the manufacturing system, with years of experience and skills in welding which contribute to the end products quality. The importance of utilizing those skills when finding a new system for automated welding led to searching for other solutions, oriented towards HRC and a hybrid workstation for a robotic and human welder.

All these observations and analyses led to formulating three proposals for how to proceed with improving Tokvam's welding system. One is to replace the current robot welding cell as initially suggested by either the robot welding system from S1 or S2. Proposal two is a re-organization of the current jig system. The author suggests a 5S-workshop to set the foundation for a thorough integration of all jigs into the company's ERP system and to establish standardized processes for the whole lifetime of a jig. The third proposal is to add a hybrid welding system instead of replacing the current robot welding system. This proposal aims to utilize the skills of more employees by using a welding-teaching system that requires less expertise in robot programming than traditional teaching methods. This, besides being faster than traditional methods, enables a better access to robotic welding for engineering and for parts which might have before not been programmed due to the long set-up time of the old welding cell.

Finally, the author recommends to opt for both: to systematically reorganize jigs and to invest in a hybrid welding station as an additional workplace in the manufacturing system. After discussing the risks and opportunities of all solutions, these two not only yield the most benefits for Tokvam in many different regards. They are further by far less expensive to implement than an investment in a system as proposed by S1 or S2.

After conducting this research, the author sees potential for further research to investigate HRC in welding operations, especially in small companies like Tokvam. If the proposed solution gets implemented at Tokvam in the future, this offers a foundation for many research projects to investigate how HRC can be utilized beyond the currently proposed teaching process.

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