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Investigation of Manufacturing Method for Odd-holed Plates for Gasketed Plate Heat Exchangers

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Abstract

This report investigates and compares the possible use of different manufacturing methods in production of odd-holed plates at Alfa Laval's site in Lund. The three methods are punching with eccentric presses, abrasive water jet cutting and laser cutting, with the first two being used currently at Alfa Laval. The aim of the project is to shorten the lead times, by finding a method that is efficient and flexible. Information, both theoretical and practical, was gathered through literature and field studies, including interviews with external experts, to obtain further insight into the three methods' suitability for this process. During the project, a number of parameters were investigated such as efficiency, work environment, both in terms of safety and cleanliness, cost, quality and environmental sustainability. An analysis, based on the gathered information and the important parameters, was conducted, resulting in a score for each mentioned method. Based on internal valuing at Alfa Laval, the parameters were weighed on a scale of 1-5, depending on how important Alfa Laval considered them to be, with 1 being the least important and 5 being the most important. The analysis found laser cutting to be the most promising option, mostly thanks to its flexibility, safety, and low need for maintenance, despite some issues regarding quality, which would require further testing. Abrasive water jet cutting was deemed the second most promising, which was the option with the lowest cost, where the high need for maintenance and post-processing as well as poor ergonomic conditions decreased its score. Punching with eccentric presses received the lowest score, with high costs connected to tools and tool maintenance as well as longer set-up and lead times being major factors, even though the quality that comes with the method is generally very high.

Keywords: manufacturing methods, punching with eccentric presses, abrasive water jet cutting, laser cutting

Sammanfattning

Den här rapporten undersöker samt jämför det möjliga användandet av olika tillverkningsmetoder i produktionen av varianthålade plattor vid Alfa Lavals produktion i Lund. De tre metoderna är stansning med excenterpressar, abrasiv vattenskärning och laserskärning, där de två förstnämnda används i Alfa Lavals produktion i dagsläget. Syftet med projektet är att förkorta ledtider, genom att hitta en metod som är effektiv och flexibel. Information, både teoretisk och praktisk, har samlats genom litteratur- och fältstudier, vilket inkluderar intervjuer med externa experter, för att få djupare insikt i de tre metodernas lämplighet för den aktuella processen. Under projektet undersöktes ett antal parametrar, så som effektivitet, arbetsmiljö, både i form av säkerhet och renlighet, kostnad, kvalité och miljömässig hållbarhet. En analys, baserad på den insamlade informationen och dessa parametrar, genomfördes, vilket resulterade i ett poäng för varje tidigare nämnd metod. Baserat på intern värdering hos Alfa Laval viktades dessa parametrar på en skala av 1-5, beroende på hur viktiga Alfa Laval anser dem vara, där 1 innebar minst viktig och 5 innebar mest viktig. I och med analysen framkom laserskärning som den mest lovande tillverkningsmetoden, främst tack vare dess flexibilitet, säkerhet och låga underhållsbehov, trots vissa problem med kvalité, vilket skulle kräva vidare tester. Abrasiv vattenskärning bedömdes som den näst mest lovande metoden, vilken var metoden med den lägsta totalkostnaden, men där det höga underhållsbehovet, mängden efterarbetet samt dåliga ergonomiska förutsättningar minskades dess poäng. Stansning med excenterpressar fick den lägsta poängen, där höga kostnader på grund av verktyg och verktygsunderhåll samt längre omställnings- och ledtider var stora faktorer, trots att kvalitén som fås med metoden generellt är mycket hög.

Nyckelord: tillverkningsmetoder, stansning med excenterpress, abrasiv vattenskärning, laserskärning

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Lund, May 2023

Hanna Eklind and Johanna Schedin

Nomenclature

AWJC	Abrasive Water Jet Cutting
CA	Cost Analysis
DC	Distribution Center
GCC	Global Core Component
GPHE	Gasketed Plate Heat Exchanger
HAZ	Heat Affected Zone
PHE	Plate Heat Exchangers
SC	Service Center

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1. Introduction

1.1. Background

1.1.1. Alfa Laval

Alfa Laval was founded in 1883 by Gustaf de Laval and his partner, Oscar Lamm. The company was founded under the name AB Separator, and the product they sold at that time was milk separators. Since then, the company has expanded a lot, and are now selling a multitude of different products, including heat exchangers of many kinds, separators, and decanters. The company has also grown globally with customers in over 100 countries, 37 major production units all around the world and sales companies in 55 countries. Alfa Laval's headquarters are in Lund, Gunnesbo, where one of the company's biggest factories is also located [1].

Alfa Laval's sales are divided into capital sales, the sales of brand-new units, and after sales, the sales of spare parts and services. In the year 2022, after sales made up 26% of the company's incoming orders. Heat exchangers accounted for 37% of that. The after sales of gasketed plate heat exchangers accounted for 60% of the after sales of all heat exchangers [1].

1.1.2. Gasketed Plate Heat Exchangers

A heat exchanger can come in several different variations. Alfa Laval sells four different kinds of heat exchangers, plate, air cooled, scraped surface, and tubular heat exchangers. Plate heat exchangers (PHE) can be made in a number of different ways, such as gasketed (GPHE), welded, and brazed plate heat exchangers, all with their own functions and applications. No matter the type of PHE, they all have the same basic concept, heating or cooling one medium using another medium, separating the two with plates. The heat transfer area of a GPHE consists of a series of corrugated plates that are fitted with gaskets, in order to seal the channels and direct the mediums. The plates are then assembled between a frame plate and a pressure plate, hanging from a carrying bar. The two mediums are pumped into the GPHE in different ports, and separated by the plates and gaskets, see Figure 1 for illustration [1].

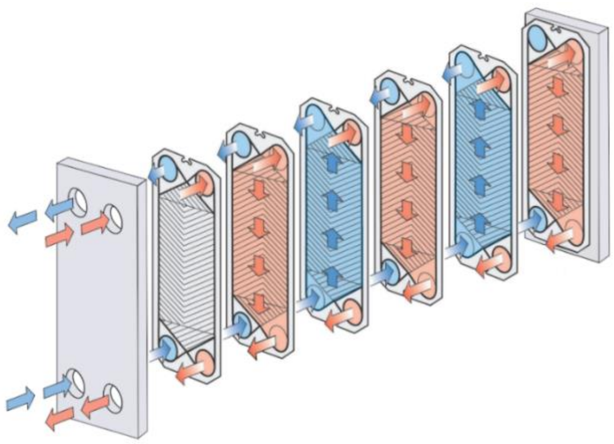

Figure 1: *Example of medium flow in a PHE [1].*

Alfa Laval's GPHE can have 16 different hole variations, as depicted in Figure 2, where the most common types are plates with four or zero holes. Zero-holed plates are typically used as end plates, whereas four-holed plates are typically used in between. However, sometimes other hole combinations are used, which are referred to as odd-holed plates, which make up 14 of the 16 different hole variations. The use of different hole variations enables a controlled flow of the mediums in the heat exchanger to meet each customer's specific needs [1].

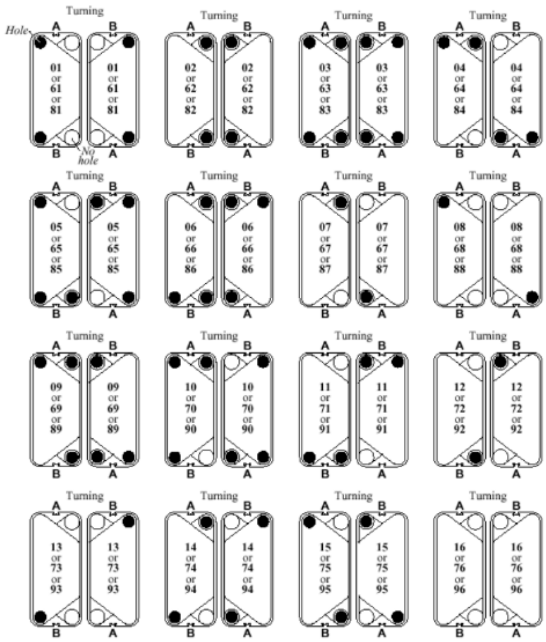

Figure 2: *Hole variations for GPHE plates [1].*

The material of the plates in a GPHE can vary a lot. The three most common materials are two types of stainless steel (304 and 316) as well as titanium. Other occurring materials are other types of stainless steel, titan-palladium, nickel and hastelloys [1].

1.1.3. Distribution Center Lund

Plates for both new units and spare part sales are produced in the factory in Lund, where the metal is cut and stamped to have the correct size and pattern, and four-holed plates are punched. The plates for spare parts are then sent to a distribution center (DC), where the plates are, if needed, punched to have the correct hole configurations (mainly the case for odd-holed plates), equipped with gaskets and in some cases hangers, and then stored to later be sent to the customer. This DC, called DC Lund, is currently located in Staffanstorp, Skåne. However, in the near future DC will be relocated to the headquarters in Lund [1].

The production in DC Lund currently uses eccentric presses for punching the holes for the GPHE plates. The largest hole size of GPHE plates reach 50 cm in diameter, however it is not possible to manufacture plates with a larger hole size than 35 cm with the current equipment. Plates with larger hole sizes are therefore manufactured in Lund, which consequently leads to longer lead times. In Lund, these plates are manufactured using punching or abrasive water jet cutting (AWJC) and are then transported to DC Lund [1].

1.2. Purpose

The objective of this report is to investigate and compare the different available manufacturing methods of making hole variations for odd-holed GPHE plates to shorten the lead time of the current production. The goal is to present a recommendation of which manufacturing method to proceed with.

1.3. Scope and Limitations

This report will investigate solutions involving the following manufacturing methods: abrasive water jet cutting (AWJC), laser cutting and punching with eccentric presses. If other methods that seem relevant are encountered during the project these might be subject to investigation as well, but focus will initially be put on the three previously mentioned methods. The solution will only apply to the manufacturing of hole variations up to 50 cm diameter in size, for the distribution center that will be relocated to Lund, Sweden from Staffanstorp, Sweden. More exact dimensions for the holes and plates can be seen in Table 1. Plates that are outside of this size range are considered irrelevant, as they are not handled by DC Lund. This makes the number of relevant plate variations around 110-130 plates [1].

Table 1: Size ranges for relevant plates *[1]*.

Dimension	*Minimum measurement [mm]*	*Maximum measurement [mm]*
Length	142.5	3400
Width	102	1500
Thickness	0.4	1
Port diameter	20	493

Since the sizes of the different plates greatly vary, they have been divided into three categories (small, medium, and large), as shown in Table 2 below. This is done to ensure that the recommended method suits all different sizes of plates, without having to investigate every single plate.

Table 2: Definition of plate sizes, based on 2022 order data *[1]*.

Parameter	*Small*	*Medium*	*Large*
Port diameter range [mm]	20-170	171-330	331-493
Share of plate types [%]	54	33	13
Share of plates ordered, DC Lund [%]	95.4	3.7	0.9

Seeing the share of plates ordered from DC Lund it can be concluded that the vast majority of plates are small plates, according to this categorization. When applied to this project, this means that it is important that the recommended manufacturing method works well for smaller plates, whereas some compromise may be acceptable for medium and large plates due to their lower production frequency. When it comes to the material of the plates, it becomes apparent that most of the plates are made in stainless steel, followed by titanium, as stated in Table 3. This makes it especially important that the chosen manufacturing method is well suited for stainless steel and titanium.

Table 3: Share of material types for ordered plates at DC Lund 2022 *[1]*.

Material	***Share of plates ordered, DC Lund [%]***
Stainless Steel 304 & 316	91.3
Titanium	7.4
Other	1.3

The three mentioned methods will be compared in terms of efficiency, work environment, cost and additional parameters that are deemed relevant, and evaluated based on the aspects that are shown in Table 4 below. The parameters have been selected in deliberation with Alfa Laval. The recommended method should produce parts that do not exceed the burring tolerance of ±0.05 mm [1].

Table 4: Parameters for evaluation of manufacturing methods.

Efficiency	**Work Environment**	**Cost**	**Additional Parameters**
Set-up time and tool change time	Safety for the operators	Initial investment, machine	Simplicity of use
Post-processing time	Impact on cleanliness in the workspace	Consumables	Quality
Additional lead-times		Maintenance	Limitations to scope of assortment
		Tools	Environmental sustainability
		Labor	

2. Methodology

This project is divided into three main parts: literature studies, field studies, and an analysis. The report thereby includes parts of both qualitative and quantitative character. The literature studies are based on theory from multiple sources, including material from the courses Sustainable Manufacturing Systems, basic and advanced course, International Product Realization, and Manufacturing Methods. Further information is also gathered from published research.

The field studies are conducted mainly at Alfa Laval's and the institution's facilities and include observations of manufacturing methods and processes as well as interviews with knowledgeable people, both within and outside of the company.

The gathering of information began with visiting the production at DC Lund to achieve a better insight into the task at hand. The current processes at the facility were observed, and discussions were had with the employees, both operators and team managers, about their thoughts on the process. This was then followed by an initial literature study, before contacting employees at Alfa Laval who have insight into different aspects of the production, and experts who were contacted via Swedish universities. Semi-structured interviews were held with the experts who have researched and/or closely worked with the relevant manufacturing method. Questions relevant to the methods were asked, which for example were about how the machine works, as well as potential benefits and problem areas that could arise if applied in the production at DC Lund. This was then followed by further literature studies, and occasional semi-structured interviews with employees as Alfa Laval, before eventually moving on to the analysis phase. The semi-structured interview consisted of a set of prepared questions which only acted as a foundation to prompt further questions and discussion. An illustrated timeline can be viewed in Figure 3.

The analysis is based on the field studies and literature studies in order to find the optimal solution and manufacturing method. The Cost Analysis (CA) is based on the conducted research and consulting with experts. The CA for each method is done for two scenarios; with an expected 7% annual production increase and with a static production volume, based on production volume data from 2022.

An equal contribution was made to the whole study and report by both authors.

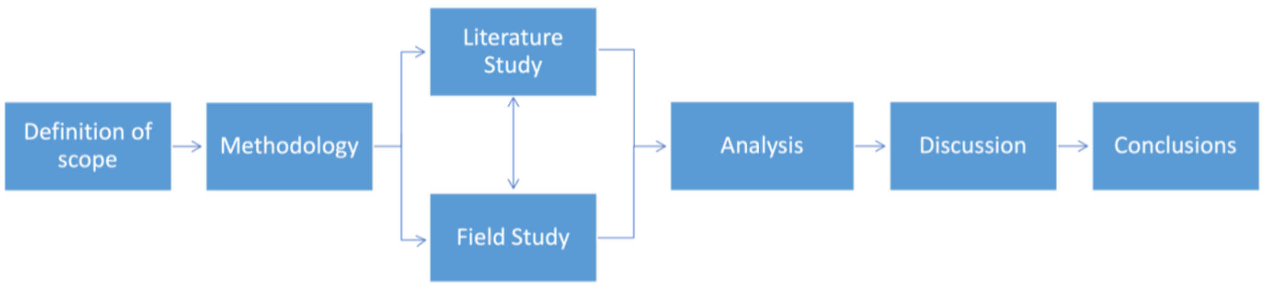

Figure 3*: Timeline of work process.*

3. Literature Study

The literature study is divided into each of the investigated manufacturing methods with the purpose of building a deeper theoretic understanding of each method. Information has been gathered from published books as well as reports and articles from reputable sources.

3.1. Abrasive Water Jet Cutting

An abrasive water-jet cutter (AWJC) is a machine that uses highly pressurized water with an added abrasive material to remove material from the workpiece. As illustrated in Figure 4, a pump is used to get the water to high pressures, and a hopper with an abrasive such as garnet adds the contents into the water stream via the mixing chamber (see Figure 5) [2]. The mixed water stream then passes through a focusing nozzle to homogenize the fluid and is then ejected towards the workpiece. The impact of the abrasives erodes the material and eventually cuts through the workpiece [3].

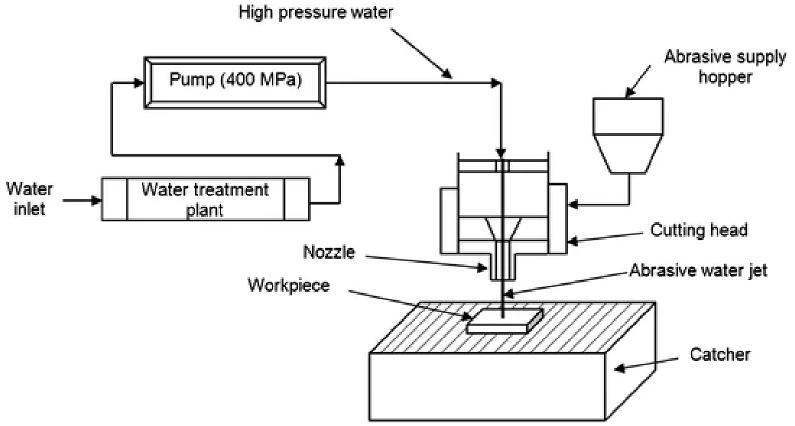

Figure 4: Schematic illustration of an AWJC system [2].

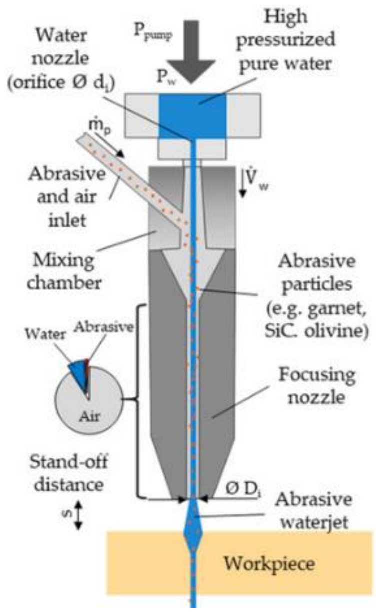

Figure 5: Illustration of an AWJC head [3].

The nozzle diameter commonly ranges between 0.5 to 1 mm, and they are often made of rubies, sapphires, and diamonds. A diamond nozzle can last up to 800 hours of running time, whereas one of sapphire can last up to 80 hours [4], however these figures differ between different sources. Water-jet pressures of 400 MPa is generally sufficient for most processes, however pressures up to 1400 MPa can be reached [5, 6].

AWJC is advantageous for processes where the workpiece is heat sensitive, as the method does not produce heat. Additionally, it can be used for single-layer and multilayer cutting and is classified as an environmentally safe manufacturing method [5]. It does not generate dust or particles that are dangerous to inhale, and the main raw material used is water and commonly garnet as the abrasive, which are inexpensive and widely available [2].

An AWJC can be used for a high variety of materials, including metals, however the cutting speed changes drastically depending on the material. The cutting speed is much lower for metals, making AWJC expensive for applications where high production rates are necessary [5]. The generation of burring is generally minimal with AWJC [5], however some can still occur due to plastic deformation that occurs when the water-jet exits the workpiece [3].

A drawback that can occur with AWJC are striation marks along the bottom of the cut surface due to a so-called lag effect. When the jet is ejected by the nozzle, the stream diverges and loses kinetic energy as the distance from the nozzle increases and cuts through the workpiece. The loss of kinetic energy causes the jet to lag along the bottom of the cut, creating striation marks. Additionally, the loss of kinetic energy can also cause a width difference between the upper and lower portion of the kerf as well as a rounded edge at the initial cut region (see Figure 6) [3].

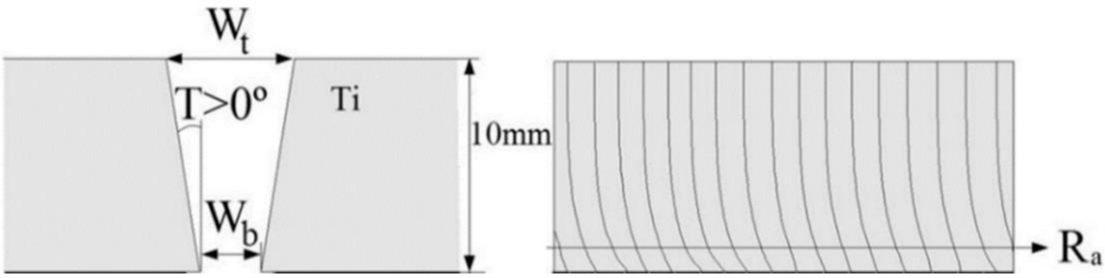

Figure 6: *Kerf width variation (left) and striation marks along cut (right), adapted from [3].*

Furthermore, AWJC can produce excessive noise, being able to reach 90 dB(A) and when in an open space can exceed 110 dB(A). One factor that can have a significant impact on the noise level is the relation between nozzle orifice diameter and focusing nozzle diameter. However, some adjustments can be made to achieve a noise reduction, such as submerging the workpiece under the water level of the tank, which reduce the noise level by 10 dB [7].

3.2. Laser Cutting

Laser cutting is a cutting method which uses thermal heating to cut the workpiece. As illustrated in Figure 7, a laser beam is led through a focusing lens and hits the workpiece, heating the surface until it either melts or vaporizes, thereby removing material and creating a cut [5].

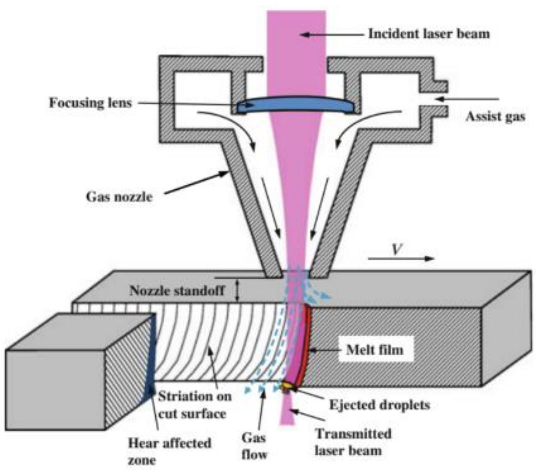

Figure 7: *Illustration of laser cutting [8].*

The laser beam is paired with a pressurized gas jet, called an assist gas, which helps to remove the melted or vaporized particles. Oxygen and nitrogen are commonly used gases for laser cutting and both work well with many materials. Using oxygen, instead of nitrogen, as assist gas often entails lower laser power, lower gas pressure and higher cutting speed. There is, however, a risk with many materials that slight oxidation occurs at the cut surface, leaving a thin oxide layer along the cut surface, causing undesired material properties such a brittleness along the cut and a worse quality of the cut edges. Oxygen also creates a more exothermic reaction, meaning that the heat affected zone (HAZ) will be bigger than when using nitrogen. This is why nitrogen is often used as assist gas when there are high demands for quality and as little impact on the material's properties as possible. Furthermore, both oxygen and nitrogen are reactive with titanium. If used, they both cause a thin oxide or nitride layer to be formed, causing the same problems as mentioned above. Helium or argon can instead be used as the assist gas for cutting titanium, preferably argon to achieve a higher quality cut as the use of helium requires a lower cutting speed and can result in wavy cut edges [8]. Because of these gases, and potential vapors coming from the workpiece melting or vaporizing, many laser cutters are built as a capsule. By doing so the surrounding factory is not subjected to vapors, gases, or radiation [9].

CO_2 and fiber lasers are the most common types of lasers, and the choice between them depends on the application for which they are intended. The two are built in different ways, as illustrated in Figure 8, and therefore work somewhat differently. The main principle is the same, using a laser beam and an assist gas to create a cut in the material. A CO_2 laser creates a laser beam by running a high voltage current through a sealed glass tube filled with a gas, usually carbon dioxide. The gas particles react with the current which increases their energy, creating powerful and warm light. Once the light is powerful enough it passes through a partially reflective mirror and is deflected via three other mirrors until it reaches the cutting head. There, the light is redirected through a focus lens onto the workpiece. It is crucial that the mirrors and lens are placed in the exact right spot for the laser beam to travel in the right way. This means that realigning these parts must be done often and thoroughly. A fiber laser follows many of the same principles that a CO_2 laser does, but a few details have been changed to make the fiber laser more practical. The laser beam in a fiber laser is created in a fiber cable and is then reflected through a narrow cavity. This narrow cavity keeps the beam extremely straight, without the use of mirrors. The laser beam is then fed into the cutting head, focused through a focus lens, and directed onto the workpiece [10].

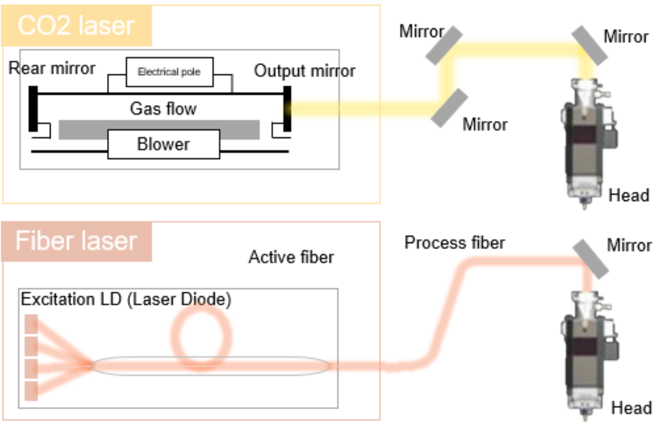

Figure 8: *Mechanisms of CO_2 laser and fiber laser, adapted from [11].*

Furthermore, there are a number of differences between CO_2 and fiber lasers when it comes to speed, cost, and overall performance. The laser beam of a fiber laser is more focused than that of a CO_2 laser and possesses greater absorption characteristics. These two aspects make it possible for a fiber laser to cut with higher speeds than a CO_2 laser, especially when cutting metals such as stainless steels, brass, and copper, with speeds up to five times greater when the workpiece is 1.27 cm (½ inch) thick or less. A fiber laser is also more economically beneficial, with a lower power consumption, around half the operating costs of a CO_2 laser, and less required maintenance. Therefore, even though a fiber laser has a larger initial investment, the return of investment time is generally shorter with a fiber laser compared to that of a CO_2 laser. In addition, a fiber laser cuts metals more safely and with higher quality than a CO_2 laser [12].

Laser cutting is generally seen as a flexible manufacturing method, mostly because it does not require any change in tools if a new type of cut is to be made. This results in the set-up time for the method being lower than many other manufacturing methods. Other than requiring a new preprogrammed route for each new hole-type that is to be made, the one thing that potentially has to be changed is the gas that is used, depending on what material is being cut [5]. The fact that no tools are used also means that the number of parts that require maintenance is low, with a fiber laser requiring even less maintenance compared to a CO_2 laser. In the cutting head there are mainly four parts that need replacing regularly, as illustrated in Figure 9. The protective lens and nozzle have to be replaced approximately every 300 hours, the TTW cable every 1800 hours and the ceramic ring every 7200 hours, based on normal usage [13, 14]. Other parts in a fiber laser cutter that require maintenance, mostly in the form of cleaning but occasionally also being repaired or replaced, are the outlet air filter and the hydraulic unit. Many laser cutters are cooled using a water-cooling system, which also requires some maintenance. This mainly includes changing the water filter once a year and changing the water in the system every six months [15].

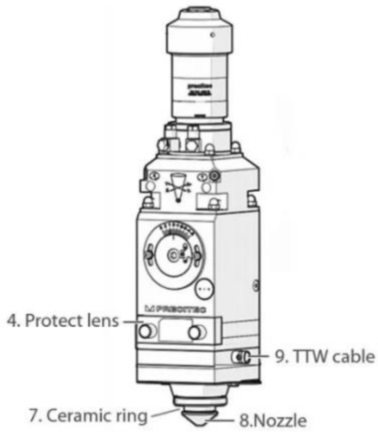

Figure 9: *Wearing parts of laser cutting head [13].*

Laser cutting has the ability to meet high tolerances. The laser beam is thinner than the edges of traditional mechanical cutting tools, often resulting in a higher accuracy [9]. Furthermore, high quality cuts can be obtained. As long as the machine is calibrated in the correct way, with regards to cutting speed, focal length, thickness of the laser beam, et cetera, the quality of the cut edges is often better than that of more traditional cutting methods, such as punching or plasma cutting. In addition, the workpiece suffers minimal deformation, such as bent edges, from laser cutting [16].

Two important things to keep in mind when using laser cutting are the thermal conductivity and the reflectivity of the material that is being cut. If a material's thermal conductivity is too high, the heat from the laser beam can spread through the material, causing a bigger HAZ, which can impact the material's properties. However, thin materials, which can be cut more quickly than thicker materials, are often less impacted by HAZ. With a highly reflective material, such as glass and aluminum, the laser beam risks bouncing off the surface and fail to cut through [5, 9]. Another important aspect to keep in mind, which mainly affects the quality of the cut, is the glancing angle, meaning the angle at which the laser beam hits the workpiece surface (see Figure 10 for illustration). An angle that diverges significantly from a 90° angle to the workpiece surface can cause striations in the cut walls. This means that for surfaces that are not flat a 3D laser cutter, a machine with a head that can move in all directions, can be required in order to obtain higher quality cuts [17].

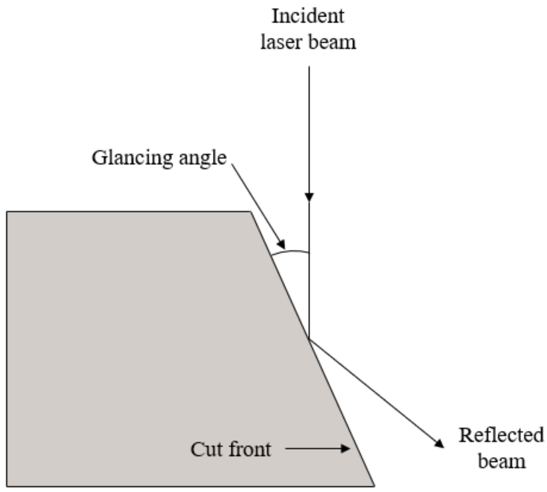

***Figure 10:** Illustration of glancing angle, adapted from [17].*

The consensus is that the noise emission of laser cutting is relatively low [18, 19]. According to Thunder Laser USA, a laser cutter vendor, the sound emitted while the machine is running is about 75 dB(A) and 55 to 65 dB(A) while idling [20].

3.3. Punching with Eccentric Presses

Eccentric presses are a type of mechanical press, which are stroke limited. The press is powered by an electric motor, where a rotary motion is translated into a linear motion [21]. It is operated by pressing a clutch which activates the motion, and the flywheel (see Figure 11) then provides the energy to perform the punching process [22]. A proper set-up of the press is essential to avoid damage to the die or component, as the available force is dependent on the stroke position, reaching high forces at the end of the stroke. They are often preferred over other mechanical press types when high precision is required, and the required skill level of the operators is low in comparison to other types of machines. Mechanical press capacities typically exist in the ranges of 2.7 to 107 MN [21].

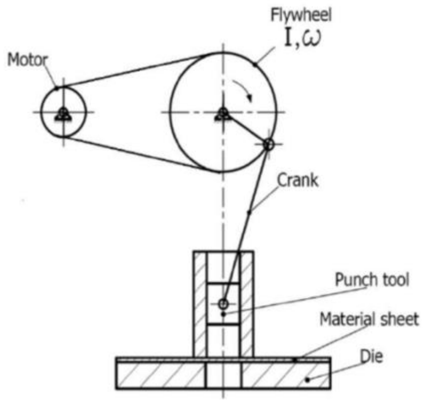

Figure 11: *Schematic illustration of an eccentric press, adapted from [22].*

Punching with eccentric presses requires a die, which can contribute to a significant cost and lead time, taking up to several months to make. Die costs depend greatly on the size, complexity, surface finish, material, manufacturing method, heat treating, and finishing methods. Separate die sets are required for different parts, where a die can cost thousands of dollars to make and are therefore commonly used for production of a large number of parts to achieve a low die cost per piece made. As the number of produced parts per die increases, the set-up time and tooling costs decrease. Additionally, long lead times to produce the dies can further contribute to higher manufacturing costs [21].

When punching sheet metal, the workpiece is subjected to shear stresses using a punch and a die. During the process, material is removed from the workpiece through crack formation, which meet and cause separation. The cracks cause a rough surface, which then becomes smooth burnished surfaces as the edges are dragged against the punch and die walls. A small clearance (see Figure 12) results in edges of greater quality, as the deformation is confined to smaller zones. Burr formation can occur along the edges, which increases in relation to increased clearance, material ductility, and dullness of tool edges [23]. Burrs can be detected through visual inspection or felt with a finger. The presence of burrs is a safety hazard for operators due to the sharp edges; burrs can cause problems such as jamming and misalignment of components during assembling; burrs can also decrease components' fatigue life. There are multiple options available for deburring, such manual deburring through filing and scraping. Manual deburring can, however, amount up to 10% of the part's manufacturing cost [5].

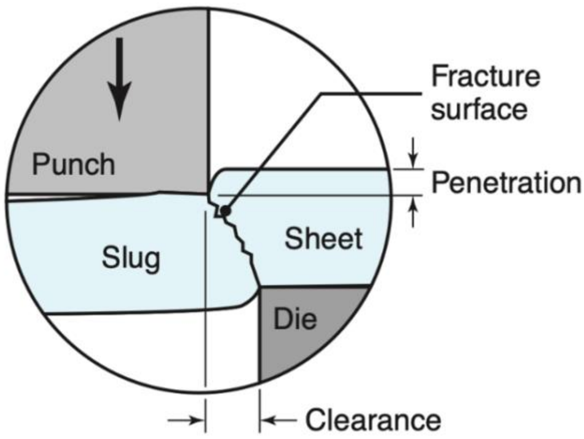

Figure 12: *Schematic illustration of clearance between punch and die, adapted from [23].*

The use of mechanical presses can produce a high noise level at the workplace. Impact noise, such as what is produced by mechanical presses, has been found to increase with increased punch sizes and impact speed. Impact noise can be difficult to measure [24], however, in a study of a punch-press shop, a median value was measured to 95 dB(A), with a peak of between 116 and 136 dB(C) [25].

4. Field Study

The field study is divided into each of the investigated manufacturing methods, which in turn are divided into information gathered through internal sources as well as external sources. Internal sources refer to information gathered through interviews with employees at Alfa Laval, as well as observations at Alfa Laval's facilities. External sources refer to information gathered through interviews with individuals who are not employed by Alfa Laval but have professional experience with the respective manufacturing methods.

4.1. Abrasive Water Jet Cutting

4.1.1. Internal Sources

4.1.1.1. SC Greenwood, US

Service Center Greenwood (SC) is a service center located in Greenwood, US. They produce, among other things, odd-holed GPHE plates for the American Distribution Center. This is done with an AWJC, equipped with one cutting head [26].

The machine that is currently used at SC can cut up to 10 plates at a time, as long as the total thickness does not exceed 5.08 cm (2 inches). Cutting the holes takes somewhere between 10 seconds and 3 minutes per hole, depending mostly on the size of the plates and hole as well as the thickness of the stack that is cut. Since SC mostly deal with low volume plates, meaning that the stack of plates is thin, it is most common that a hole takes around 10 seconds to cut. With the use of the clamps that are located on the outer edges of the work area, fixtures or weights to hold the plates in place and keep the plates from bending become obsolete. The plates are simply clamped into place. A laser is used to accurately find the starting point, instead of using probe plates, which is either at the hanger of the plate, or the center of the hole if there is no hanger. The set-up time for the process is 5-10 minutes, depending mostly on the size and number of plates. This time includes changing the cutting file, putting a new plate in plate, clamp in down, setting the correct cutting program and doing a test run for the first plate. The test run is done by cutting a faint trace in the plate, using only water and no abrasive material. By doing this, the operator can see if the cutting route is correct before making the actual cut, thereby reducing the risk for errors. If the cutting route is correct, abrasive material is added to the water stream and the same plate can then be cut, meaning that the test plate does not have to be scrapped [26].

The machine is placed openly in the production area. There has not been any need for walls or any other form of separators between the machine and the rest of the production. This has been possible since the amount of dust and moisture coming out from the machine is minimal. The maintenance that is done on the machine, cleaning, changing broken parts, et cetera, is predominantly done by in-house personnel. The people doing this have gone through training provided by the supplier of the machine [26].

There is some post work that is required after this process. The main thing is cleaning and drying the plates once they come out of the machine. Since an abrasive material is added to the water, this material must be rinsed off before the plates can be fitted with gaskets and sent to customers. This is done with a normal water hose, and the plates are then put in a rack to dry, sometimes with a big fan to speed up the drying process. Deburring may also be required, which is done manually [26].

4.1.1.2. GCC Lund, Sweden

Global Core Component (GCC) Lund is the main Swedish production site of GPHE. The production includes manufacturing of odd-holed of plates, one of which uses an AWJC. The current machine is from another brand than the machine in SC. It has four nozzle heads and operates on 3-axis. The current set-up uses fixtures to hold the plates in place. Each plate type requires its own unique fixture, which are stored on nearby pallet racks. The fixtures typically have probe holes, which are utilized to find the exact plate location and hole placement. The AWJC is enclosed in an isolated area, approximately 130 square meters in size, due to the humid environment and particles from the garnet that may spread into the air [27].

The machine is handled by one operator. Due to the wet surface area after the cutting procedure, transportation of the plates to and from the workbench cannot be done with the use of suction cups and is instead done manually. Large plates are transported to the workbench through maneuvering the plate close to the machine with a forklift and transferring it on manually [27].

Stacks of up to five plates can be cut simultaneously, however three is the typical amount depending on the plate type. To ensure a correct cut, weights are sometimes placed on top of the plates to prevent bending and ensure that the plate remains straight. Since the plates have a thin film of lubrication from previous processes specific to GCC Lund, some problems of fine abrasive particles require more extensive cleaning to remove than for a typical clean plate. This creates longer lead times due to external cleaning processes, which are not directly applicable to lead times for cleaning the plates at DC Lund. Before doing the actual cut on a plate, GCC does a test run in the same way as SC does, to ensure that everything is correct before cutting the plate [27].

High nickel-values in the water output have been observed, which emphasizes the need for a filtration system in the case of an investment in a new AWJC. Additionally, it is important to consider how washing of the plates would be conducted after the cutting procedure, since any residual garnet on the plate needs to be removed [28].

4.1.2. External Sources

To achieve a better insight into AWJC, Christian Öjmertz was consulted with, who has previously done research on the subject and currently owns an AWJC company.

Different important aspects and factors to consider when using AWJC were discussed. Firstly, the water quality is important since impurities can negatively impact machine equipment. Impurities that are in hard water, meaning water with high levels of minerals such as calcium and magnesium, can build up in the nozzle and eventually break off, wearing out the equipment. Furthermore, the quality of the garnet is important to consider, as this can affect the working environment and the equipment. Poor quality garnet may contain an abundance of fine particles, which can spread into the air, negatively affecting the air quality for the operator and can interfere with sensitive operations in the near vicinity of the machine. The fine particles can also cause build up the nozzle and wear the equipment out at a higher rate [29].

AWJC has the benefit of being able to cut through many different materials without the need to change the equipment in between, thereby minimizing the set-up time. The method also allows you to cut through multiple layers. Burring can occur for materials with high ductility, but the materials that are relevant to the project have a low degree of burr formation. Taper can, however, occur, meaning that there is a difference in width of the top and bottom of the cut. Some calibration can be done to minimize this occurrence, but it can be further eliminated with a 5-axis AWJC to compensate the angle of the taper to achieve a straight cut and can additionally allow a higher cutting speed. Modern AWJC systems are deemed to be easy to use and tolerances of approximately ±0.1 mm can be achieved from conventional machines [29].

Since the manufacturing method is a wet process containing small particles, it is important that the particles are cleaned off before the product has dried, to prevent the particles from adhering to the product. For applications where it is highly important to ensure that there are no residue particles, the product can be washed in an ultrasonic bath. It is also generally recommended to enclose the machine in an isolated enclosure to protect nearby sensitive equipment from humidity and particles [29].

When determining what type of AWJC machine is appropriate, the amount of actively cutting nozzles can be considered. Multiple nozzles can allow more products to be cut simultaneously. However, if a blockage occurs in one nozzle it will make all nozzles unfunctional until resolved. If all nozzles are not utilized, humidity can cause blockage of the other nozzles. Additionally, 5-axis angle compensation may not be possible to utilize with the use of multiple nozzles [29].

The general lifetime of an AWJC machine is estimated by Öjmertz to be approximately 10 to 20 years, however, additional maintenance needs to be done as well. General maintenance such as changing nozzles and focus tubes can be done by the operator. Some equipment that without special training would require an external party to provide service on would be of the pump seals after 500 hours of running time and pump cylinders after 5000 hours of running time [29].

4.2. Laser Cutting

4.2.1. Internal Sources

There have been several tests of laser cutting carried out for a similar project conducted at Alfa Laval that is looking into possibly replacing a water jet cutter with a laser cutter for GCC, Lund. There are a few take aways from these tests and the project in general that can be applied to this project.

Some of the tests show that it is possible to cut plates with smaller gaps (the height between the bottom and the top of the pattern of the plate) at a constant height between the nozzle and the surface of the plate, while still meeting high quality demands. If the gaps are small enough the nozzle could potentially remain at a constant height, instead of following the pattern of the plate. This would save time during the actual cutting and reduce the risk of impact between the nozzle and workpiece. For larger height variations, the nozzle will have to follow the height variations as well as compensate for the angles. Without angle and height compensation, it has been found that the resulting burring deviates from Alfa Laval's accepted tolerances. It has also been shown that finding the correct cutting parameters is vital for the quality of the cut. If a laser cutter was to be implemented at Alfa Laval, some sort of external expertise would most probably be required to initially configure the machine correctly [28].

It has also been found that a specially designed table would be required for this type of cutting process. Traditional cutting tables consist of a large number of spikes, mounted together to create a surface for the workpiece to rest on. When one of these spikes is hit by the laser beam, splashes of molten metal occur which end up on the plate. These splashes normally have to be grinded away. Doing this is, however, not possible in this case since the plates have already been pressed to have the correct plate pattern and could be damaged by this type of grinding. Therefore, a specially designed table would have to be ordered, that either lets the operator manually remove sections of these spikes, that follows the laser beam and automatically retracts them where the cutting occurs or that compensates for this in some other way. There are tables similar to this available on the market, but they do come with an additional cost to the initial investment [28].

Since it is a dry process, support equipment such as suction cups can be used for lifting and transporting the plates, enabling a more ergonomic working procedure for the operator. It can also be noted that the amount of post work required after laser cutting is smaller than that after water jet cutting, provided that the machine is calibrated correctly. With the right cutting parameters and equipment, post-processing such as deburring, grinding, or washing could be avoided. However, equipment such as external sensors to compensate angle and height variations across the plate would be required, since the use of 3D files is not available to configure this in the cutting route [28].

4.2.2. External Sources

To receive additional input about laser cutting, Alexander Kaplan, a researcher in laser cutting and professor in Manufacturing Systems Engineering at Luleå University of Technology, was consulted with.

One area of interest that was discussed was regarding issues that could arise due to the different plate materials. As presented in the literature study, laser cutting can be problematic with reflective materials. However, with the materials in question, this issue can be disregarded for the application. If any issues were to occur, the problem could be overcome with a pre-drilled hole at which the laser could initiate the cutting process [30].

Additional interest areas that were discussed but deemed to be unproblematic for the application were HAZ, with the justification that the material thickness is relatively small; burring and finishing work were also disregarded, as the thin material should not result in deviations from the set tolerances; multiple wavelength ranges of the laser, which would require an additional machine, should not be required for the relevant materials. Laser cutting is typically a larger initial investment than more traditional manufacturing methods, it can, however, long-term be financially beneficial due to its flexibility and low need for maintenance. Maintenance that can occasionally be required is change of optics [30].

When speaking with a vendor from Trumpf, a laser cutting company, some further insights were given. When handling a variety of different materials in the laser cutter, it is important to be aware of the risks that could entail and to take proactive measures to eliminate the issues. When changing between different materials, an explosive hazard can occur due to the buildup mixing in the filters. This risk can, however, be minimized by following frequent procedures of changing filters and cleaning the machine regularly [31].

The laser cutter has a large initial cost, where external sensor equipment is needed to control the height and angle of the nozzle as 3D files are unavailable for the GPHE plates. However, it is relatively maintenance free during its lifecycle. Running costs for a laser cutter involves gas consumption and electrical costs, as well as maintenance of typically once per year. A benchmark value for an approximate machine lifetime is 20 years [31].

4.3. Punching with Eccentric Presses

4.3.1. Internal Sources

4.3.1.1. DC Lund

DC Lund uses three eccentric presses for hole punching. As of right now, the machines at DC Lund are too small for the plates that they are intended to punch in the future. The machines that are in DC Lund today can make holes with a maximum diameter of 350 mm, but the maximum diameter intended in the future is 493 mm [1]. This means that another machine would have to be purchased in order to meet the assortment that is planned to be punched at DC Lund later on.

Besides these presses DC Lund also have many tools connected to the presses, such as dies. These must be individualized for each type of plate, and sometimes up to three different dies are required per plate. This means that there is a large stock of dies, which both take up a lot of space and cost quite a lot of money. The smaller and more frequently used dies are kept close to the workstation while the bigger and less frequently used ones are kept further away from the machines. These have to be retrieved using a forklift, which can be time consuming. Besides this, a considerable amount of money is tied up in these dies. The dies also require some maintenance, mostly sharpening the edges. If the edges become too dull, some burring will start to show on the punched plates. The plates are controlled manually for burring, by looking at and feeling the punched edges. Once burrs start to occur, usually after around 2000 punches, the operators know that it is possible to punch around 20-50 more plates before the burrs are too severe to pass quality control, at which point it is time to sharpen the tools. It normally takes around 1-3 weeks to send a tool to the tool shop to be sharpened [32].

Another factor that takes a significant amount of time in DC Lund is changing the tools between each type of plate that is punched. Because of the low volumes, the tool can be changed up to 20 times each day. Since the change itself takes around 10-15 minutes, there is substantial downtime connected to tool change. Once all the tools are in place the method is, however, efficient, with one hole taking less than 5 seconds to make [32].

The eccentric presses in DC Lund are quite old and were bought sometime in the ‘70s. Maintenance and some minor renovations have been done to the machines since then (switching belts, upkeeping the brakes, changing parts of the clutch, et cetera) but they have overall stayed in good condition. Accidents with the eccentric presses at DC Lund are rare, however it has occasionally occurred. A recent accident has prompted concern for the risk involved of using mechanical presses and crush injuries [32].

4.3.1.2. GCC Lund

At GCC Lund there are two smaller eccentric presses in the smaller production line and one bigger eccentric press in one of the assembly lines. The two smaller eccentric presses punch holes ranging from 20 mm to 140 mm in diameter, and the bigger eccentric press punches holes up to 350 mm in diameter. Whether a plate is punched in the smaller or bigger production line is determined by the diameter of the hole and by the dimensions of the plate itself. Some of the bigger plates that are punched in the bigger punch, with lengths up to 2600 mm, require two operators working together and a support table placed in the middle of the plate, in order for the operation to be possible. With the current production set-up it is not practically possible to punch plates that are bigger than the ones that are currently being punched. In the smaller production line plates with lengths up to 1500 mm are punched, which can be handled by one operator [33].

There is a large number of dies required for the punching operation at GCC. Each plate type has at least two dies per plate, to be able to punch the holes correctly. Besides being a costly investment, they also occupy an extensive amount of space. The dies are stored in pallet racks, with 24-27 dies each depending on the size of them and pallet racks, taking up 6-8 square meters per rack. Some bigger dies that are rarely used have to be stored in another location and are retrieved using a truck when needed. This takes up a significant amount of time and can halt production of certain plates for up to a day while waiting for the correct dies to arrive. Furthermore, the dies are heavy and can weigh upwards of 230 kg. Despite accidents being extremely uncommon the dies can still pose a risk to the workers, especially during tool change. During tool changes, the dies are placed in front of the eccentric press with a forklift and then pushed into place by the operator. This can put a strain on the operator, and with tool changes being done up to 20 times a day it risks becoming a repeated, strenuous operation [33].

The most common issue that occurs with the eccentric presses at GCC Lund, though it is quite rare, is burring, which is a result of the tools not being sharp enough. The plates are manually checked for burrs, by touch and visual inspection. The aim is the send the tools for sharpening once every 1-2 weeks, to maintain sharp and well-functioning tools. However, with it taking around 1-3 weeks for the tools to be sharpened, it is not practical to do so consistently [33].

At GCC Lund there is also a tool workshop, that makes and maintains many of the tools that are used. The average cost of making a new die is around 140 000 SEK for a small die and 170 000 SEK for bigger ones. The cost for sharpening and maintaining the tools is around 25 000 SEK to 30 000 SEK per die [34].

4.3.2. External Sources

To gain additional insight into punching with eccentric presses, Nader Asnafi, who is knowledgeable within traditional manufacturing methods, such as punching, was consulted with.

Regarding the life span of an eccentric press, it was stated that they, in theory, can hold up for virtually forever, given that the machine is of good quality. Since it is a mechanical process, the only thing that would have to be done is replacing parts that are worn out, such as breaks and dies. This means that machines that are already 50 years old, and more, should still be perfectly usable for many years to come, provided that they get the maintenance they require. The advantages with buying a new eccentric press would be that they are often quieter, safer, and slightly more advanced. The basic principle of the new machines is still the same, however [35].

The biggest advantage with punching using eccentric presses is the low machine cost per hole made. Even though some tools can be quite expensive, and many tools can be required, the initial cost for the machine is relatively low. This in combination with the method being effective, means that the machine cost per hole made is low [35].

The problems that can occur when punching with eccentric presses are mostly related to the quality of the workpiece. One issue that can occur is burring, which would have to be removed, often manually, after the hole is made. Another problem is with the surface from which the hole is punched. Since this method uses brute force to create the hole, there is a risk that the remaining surface is slightly bent or deformed after the punching operation. This is something that not only risks affecting the quality of the plate itself, but also the functionality and flow of the entire heat exchanger. A third problem that can arise is angled walls in the cut. Lastly, there is a risk that the mechanical properties of the material are affected. Because of the shear force that is applied to the workpiece during the punching process, the material at the edge can harden [35].

5. Analysis

The analysis is based on information that has been gathered in the literature study and the field study. The three methods will be compared against each other on several different criteria; efficiency, work environment, cost, and additional parameters.

5.1. Efficiency

The comparison for the efficiency of each of the manufacturing methods' different parameters were subjected to investigation: set-up time and tool change time, as well as post-processing time.

<u>Set-up time and tool change time</u>

Set-up time refers to the time required to prepare the machine to produce the next batch, whereas the tool change time refers to the time required to change a tool that is worn and needs to be replaced or resharpened.

For a fiber laser cutter, there are no tools in direct contact with the workpiece, and the tools are subjected to very little wear, leading to next to no tool change time. There is some set-up time required (see Table 5), such as time to change the gas type if a different material is to be cut, and input of the correct cutting program for the specific plate. The plates also must be placed into position in the machine.

Table 5: Set-up time for each manufacturing method.

	AWJC		***Laser cutting***		***Punching***	
Plate size	Small	Medium & large	Small	Medium & large	Small	Medium & large
Set-up time [min]	5	10	4	5	10	15

As with laser cutting, there are no tools in AWJC that are in direct contact with the workpiece, however due to the use of abrasive particles, parts of the tools such as the nozzle and focusing tube are subjected to more wear. Because the annual production is relatively low, the need to change the tool due to wear would be infrequent. This makes the tool change time for AWJC not significantly higher than for laser cutting. It should, however, be noted that clogging can occur in the nozzle, prompting the operator to unclog it or replace it if needed, which could occur more frequently if a poor-quality abrasive is used. There is set-up time required as well (see Table 5), assumed to be slightly longer than for laser cutting as the plates need to be secured with a clamp to keep the workpiece in place throughout the cutting process, and then some time required to choose the correct cutting program for the plate. AWJC, however, has the benefit of being able to cut through a stack of plates, which could compensate for the longer set-up time.

Out of the three methods, punching with eccentric presses is the one with the longest time to set-up (see Table 5), since each plate requires a unique tool. Depending on the size of the tool, and how near the tool is located to the machine, the set-up time can be relatively long and is longer than those for laser cutting and AWJC. Tool change time can also be significant.

Post-processing time

Post-processing time refers to the time required after the cutting process to achieve an end-product that fulfills all requirements.

The biggest risk with all three methods is the risk of burring during the cutting process. How much time that is required for the deburring depends on the size of the hole and the severity of the burr. How much lead time that is added to the production is dependent on whether this is done in-house or by a subcontractor. Any deburring in the current production of GCC Lund is done by a subcontractor, which if continued for DC Lund as well would add additional lead times and costs to the production.

Based on the current production at DC Lund, no deburring is required when punching with eccentric presses, provided that the dies are sufficiently sharpened. AWJC may require some deburring, with reference to the production in GCC Lund. Some of the results from tests conducted with laser cutting have not provided sufficiently small burring, however it is still believed that sufficient results could be achieved. Depending on the results from further testing, laser cut plates may or may not require post-processing in the form of deburring.

Additionally, AWJC would require further post-processing of cleaning and drying the plates, since they are subjected to water and abrasive particles during the cutting. The residual abrasive particles would need to be washed off before the plate has dried for easier removal, and the plate would then need to be dried with fans or in room temperature.

Additional lead-time

For punching with eccentric presses, there are additional lead-times due to tool maintenance. Because the tools are in direct contact with the workpiece, the edges of the die eventually become dull, leading to more burring. This requires the tool to be sent to the tool workshop for resharpening, which adds a lead-time of one to three weeks. This could potentially halt production if the plate type for the specific tool is ordered while away unless there are duplicate tools.

AWJC also causes additional lead-times due to maintenance, where sanitation of the machine is done every 12 weeks if the same routines are used as with the AWJC at GCC Lund. Sanitation causes downtime of approximately two shifts to complete the sanitation.

Laser cutting is assumed to cause downtime for maintenance once per year over two shifts.

5.2. Work Environment

Safety for the operators

Safety for the operators refers to risks that the operator might be subjected to in connection to the machine. This includes factors such as noise pollution, ergonomics, air quality, and risk of bodily harm.

Regarding noise pollution of the work environment, AWJC is infamous for the noise produced during the cutting process. According to the Swedish Work Environment Authority, the average noise level throughout the day should not exceed 85 dB(A) and the peak noise level should not exceed 135 dB(C) and 115 dB(A) [36]. Consistent exposure to noise pollution can lead to effects such as stress, hearing loss, sleep disruption and headaches [37]. Due to the high noise level that can occur with AWJC, hearing protection will be necessary for employees in the near vicinity of the machine. Punching with eccentric presses produces high impulse noise levels, which would also require hearing protection. The noise emitted from a laser cutter is, however, comparatively low and is unlikely to require hearing protection.

Another risk with AWJC, which is not the case with the other two investigated methods, is the inability to use lifting equipment such as suction cups, which often results in the operator manually pushing the larger plates into place. This can be a bad ergonomic situation, which can lead to problems such as musculoskeletal disorders, back, neck and shoulder pain, and fatigue [38]. This is less of an issue with laser cutting and punching with eccentric presses since they are dry processes, enabling the use of suctioning lifting equipment for larger plates.

There are different other risk factors involved for each of the investigated manufacturing methods. With a laser cutter, harmful fumes can be created, however, with modern machines, these are enclosed inside the machine and filtered, with insignificant risk of the fumes reaching the operators. Punching with eccentric presses involves risk of body parts being crushed. There are safety measures on the machines to avoid this risk, such as magnetic locks and light beams which stop the machine when broken, however if the machine is improperly used, they can be overcome. This directs some safety concern towards eccentric presses as there has occurred accidents, albeit the number of work-related injuries at Alfa Laval facilities that use eccentric presses for punching and AWJC are low.

Impact on cleanliness in the workspace

With the use of abrasive particles in AWJC, fine particles can end up in the air and thereby spread out in the work area in its near vicinity. This method could therefore affect the cleanliness of the workspace, causing disturbances to more sensitive processes and operations in the vicinity. Punching with eccentric presses and laser cutting are, however, deemed to have a negligible effect on the cleanliness of the workspace.

5.3. Cost

To examine which of the different manufacturing methods is the most financially feasible option over time, a CA was conducted. The input values for the calculations are based on assumptions based on information gathered through the literature study and the field study. The costs that are covered in the CA are the initial cost of investment of the machine, consumables (garnet and assist gas), tools, maintenance, and labor. The production volume is expected to increase 7% annually [39], which affects variable costs such as costs for labor, garnet consumption, assist gas consumption and tool wear.

Costs regarding the initial cost of investment refer to large costs that are critical to carry out the operation, such as the machine and tools. Consumables refer to garnet for AWJC and assist gas for laser cutting and are continuous costs throughout the life cycle.

Maintenance is assumed to be made based on a preventative method and thereby conducted based on the number of operated hours. This can reduce the occurrence of unplanned downtime; however, it also implies the risk of replacing parts that may still be operable.

The different machines are assumed to only be used for the production at DC Lund. The total annual cutting time therefore only reflects the odd-holing of plates at DC Lund.

Calculations of cutting speed assumes cutting plates with an average thickness of 0.618 mm, based on order data at DC Lund 2022.

The cost of labor for the three different manufacturing methods are based on the number of required operators, total time that can be connected with each method, and an hourly cost per operator of 345 SEK. AWJC and punching with eccentric presses are assumed to require one operator for small and medium plates and two operators for large plates. Laser cutting is assumed to require one operator, regardless of the size of the plates. This assumes that lifting gear with suction cups, or similar, can be used to place the plate in place for laser cutting, whereas more manual work would be required to handle large plates for the other methods. The costs of labor for each method only reflects the cost that is directly connected to the machine, such as active cutting time, set-up time and post-processing time. It does not reflect time the operator spends doing other tasks.

It is worth noting that one-time costs such as transportation and installation of machines and training operators are not included in the following CAs. This is because such costs often vary quite much between different suppliers and depend greatly on what deals are made between supplier and buyer.

5.3.1. Abrasive Water Jet Cutting

Results from the CA for AWJC are presented in

Table ***6***, where maintenance and labor are the greatest cost drivers. The lifespan of the AWJC is assumed to be 20 years, as the total annual active cutting time is relatively low, which leads to a lower wear rate of the machine. A suitable 5-axis machine is estimated to require an initial investment of 3 MSEK.

Table 6: Key values from CA for Abrasive Water Jet Cutting, given in kSEK, with a 7% annual production increase.[1]

Cost parameter	2024	2025	2026	…	2041	2042	2043	Accumulated after 20 years
Initial investment (machine)	-3 000	0	0	…	0	0	0	*-3 000*
Consumables (garnet)	-15	-16	-17	…	-47	-51	-54	*-615*
Maintenance	-660	-660	-660	…	-760	-660	-662	*-13 309*
Tools	-9	-9	-9	…	-37	-32	-35	*-428*
Labor	-251	-268	-287	…	-792	-848	-907	*-10 282*
Total	***-3 935***	***-953***	***-973***	**…**	***-1 637***	***-1 591***	***-1 658***	***-27 634***

Costs regarding consumption of abrasive material, which is assumed to be garnet, is calculated based on a flow rate of 320 g/min, garnet cost of 5 SEK/kg and a cutting speed of 344 mm/min for a stack of 4 plates with average thickness. The cutting speed is based on the current AWJC at GCC Lund for stainless steel plates and is assumed to not differ for titanium. The portion of plates made from other materials is very small and is assumed to have a negligible effect on the overall cutting speed. The cutting speed, as well as quantity and measurements from 2022 order data on spare part production handled by DC Lund were used to calculate an approximate annual active cutting time of 150 hours, which increases 7% annually.

Maintenance costs of the machine includes sanitation of the machine and replacement of machine parts. The parts included in the CA are pump seals; hand valves, connectors, and final filter; high-pressure cylinder for the pump; pressure accumulator for the pump. The cost and operational lifetime for each respective part is presented in Table 7. Sanitation is estimated to be required every 12 weeks, at a cost of 55 kSEK per occurrence. The annual cost of maintenance is calculated based on the active cutting time, the operational lifetime of the parts, the respective costs as well as sanitation costs. In 2041, replacement of the high-pressure cylinder in the pump is expected, leading to a higher cost than other years. Additionally, it should, however, be noted that the accumulated active cutting time over 20 years does not exceed the lifespan of the pressure accumulator and therefore it has not contributed to any costs.

Table 7: Cost and lifetime of machine parts for AWJC, adapted from *[4]*.

Maintenance, spare parts	Cost [kSEK]	Operational lifetime [hours]
Pump seals	0.08	500
Hand valves, connectors, and final filter	2	1500
High-pressure cylinder, pump	100	5000
Pressure accumulator, pump	100	10000

[1] The values shown in the table are rounded to the nearest whole number, which might affect the appearance of the total sum.

Parts in the cutting head of the AWJC are referred to as tools for the CA and are parts that are subjected to a high degree of wear. The tools include the mixing chamber, focusing tube, and diamond nozzle. The annual tool cost is calculated on the active cutting time, the operational lifetime of each tool and the respective costs (see Table 8), of which the focusing tube is the largest cost driver.

Table 8: Tool cost and lifetime for AWJC, adapted from *[4, 40]*.

Tools	***Cost [kSEK]***	***Operational lifetime [hours]***
Mixing chamber	2	500
Focusing tube	3	50
Diamond nozzle	5	700

Labor cost, in addition to the active cutting time, is based on the required set-up time per batch as well as post-processing consisting of washing every plate after the cutting process. Small plates are estimated to require five minutes for set-up time, whereas medium and large plates are estimated to require ten minutes for set-up time as they are more labor intensive to move into place (see Table 5). The number of batches are based on the number of orders at DC Lund 2022, which results in a total set-up time of 356.3 hours per year, which increases 7% annually. For post-processing time, small plates are estimated to require a half minute, whereas medium and large plates are estimated to need one minute, which includes washing the plate and placing it to dry. This results in a total post-processing time of 154.5 hours per year, which increases 7% annually.

With a static production volume, the key values from the CA are instead as shown in Table 9, where the total accumulated cost is 21.7 MSEK.

Table 9: Key values from CA for AWJC, given in kSEK, with a static production volume.[1]

Cost parameter	***2024***	***2025***	***2026***	***…***	***2043***	***Accumulated after 20 years***
Initial investment (machine)	-3 000	0	0	…	0	*-3 000*
Consumables (garnet)	-15	-15	-15	…	-15	*-300*
Maintenance	-660	-660	-660	…	-662	*-13 204*
Tools	-9	-9	-9	…	-11	*-212*
Labor	-251	-251	-251	…	-251	*-5 016*
Total	***-3 935***	***-935***	***-935***	***…***	***-939***	***-21 733***

5.3.2. Laser Cutting

Results from the CA for laser cutting are presented in Table 10, where the initial investment and assist gases are the greatest cost drivers. The total annual active cutting time is relatively low with the laser cutter, which leads to a lower wear rate of the machine. The lifespan of the

[1] The values shown in the table are rounded to the nearest whole number, which might affect the appearance of the total sum.

laser cutter is thereby assumed to be 20 years. A suitable 3D-cutting machine with a sensor to compensate for height and angle variations in the plate as well as a cutting table which fulfills all the process's requirements is estimated to require an initial investment of 15 MSEK.

Table 10: Key values from CA for Laser cutting, given in kSEK, with a 7% annual production increase. [1]

Cost parameter	*2024*	*2025*	*2026*	*…*	*2043*	*Accumulated after 20 years*
Initial investment (machine)	-15 000	0	0	…	0	*-15 000*
Consumables (assist gas)	-598	-640	-685	…	-2 162	*-24 510*
Maintenance and tools	-55	-55	-55	…	-55	*-1 100*
Labor	-165	-177	-189	…	-598	*-6 775*
Total	***-15 818***	***-872***	***-929***	***…***	***-2 815***	***-47 386***

Costs connected to the annual consumption of assist gas for laser cutting are calculated based on an average cutting speed of 1 m/min when cutting titanium and 2.37 m/min when cutting other materials and an annual cutting distance, based on 2022 data for the assortment scope cut at DC Lund and orders sent from DC Lund to GCC Lund. The flow rate of assist gas when cutting titanium (using argon) was determined to be 0.757 m^3/m and 0.17 m^3/m when cutting all other materials (using nitrogen). The cost of these gases is 224 SEK/m^3 for argon and 122 SEK/m^3 for nitrogen [41].

The maintenance cost for a laser cutter includes costs for both the laser cutter itself and a cooling system for the machine. The parts included in the CA are air and water filters, parts and maintenance of the machine's hydraulics, protective lenses, nozzles, focus lenses, ceramic rings and TTW cables. The operational lifetime for each respective part is presented in Table 11. Maintenance such as cleaning and changing the parts that are shown in Table 11 should be done periodically and are often done and charged for together. Because of this, individual costs of each part are difficult to find, and therefore maintenance and tools have been added into one cost in the CA for laser cutting.

Table 11: Lifetime of machine and wearing parts of laser cutter [13, 14, 15].

Maintenance, spare parts	*Operational lifetime [hours]*
Air filter	Change once a year
Water filter	Change once a year
Hydraulic	Change once a year
Protective lens	300
Nozzle	300
Focus lens	Change once a year
Ceramic rings	7200
TTW cable	1800

[1] The values shown in the table are rounded to the nearest whole number, which might affect the appearance of the total sum.

Labor cost is, in addition to the active cutting time, based on the required set-up time per batch. Small plates are estimated to require four minutes for set-up time, whereas medium and large plates are estimated to require five minutes. The number of batches are based on the number of orders handled at DC Lund and orders sent from DC Lund to GCC Lund during 2022, which results in a total set-up time of 291.1 hours per year, which increases 7% annually.

With a static production volume, the key values from the CA are instead as shown in Table 12, where the total accumulated cost is 31.36 MSEK.

Table 12: Key values from CA for Laser cutting, given in kSEK, with a static production volume.[1]

Cost parameter	*2024*	*2025*	*2026*	*…*	*2043*	*Accumulated after 20 years*
Initial investment (machine)	-15 000	0	0	…	0	*-15 000*
Consumables (assist gas)	-598	-598	-598	…	-598	*-11 958*
Maintenance and tools	-55	-55	-55	…	-55	*-1 100*
Labor	-165	-165	-165	…	-165	*3 305*
Total	***-15 818***	***-818***	***-818***	***…***	***-818***	***-31 363***

5.3.3. Punching with Eccentric Presses

Results from the CA for punching with eccentric presses are presented in Table 13, where new tools and tool maintenance are the greatest cost drivers. An eccentric press of good quality that is maintained regularly has an expected lifespan of at least 40 years. Since a bigger eccentric press than the current ones would have to be bought in order to be able to punch the entire scope of assortment this makes the initial investment slightly higher than the initial investment of the existing eccentric presses were.

Table 13: Key values from CA for Punching with Eccentric Presses, given in kSEK, with a 7% annual production increase.[1]

Cost parameter	*2024*	*2025*	*2026*	*…*	*2035*	*…*	*2043*	*Accumulated after 20 years*
Initial investment (machine)	-600	0	0	…	0	…	0	*-600*
New tools	-12 724	-141	-283	…	-141	…	-141	*-16 638*
Tool maintenance	-544	-582	-623	…	-1 145	…	-1 967	*-22 300*
Machine maintenance	-1 009	-288	-288	…	-396	…	-288	*-6 589*
Labor	-304	-326	-348	…	-641	…	-1 101	*-12 478*
Total	***-15 182***	***-1 337***	***-1 542***	***…***	***-2 323***	***…***	***-3 497***	***-58 651***

[1] The values shown in the table are rounded to the nearest whole number, which might affect the appearance of the total sum.

In order to be able to punch the entire scope of assortment new tools will have to be purchased, with a cost of 140 000 SEK for tools for small to medium plates and 170 000 SEK for tools for large plates. There is currently a quite large gap between the existing tools in DC Lund and the assortment of plates that are to be punched, and it is estimated that 90 new tools would have to be purchased, based on order and manufacturing data from DC Lund in the years 2020-2022, which drives up the cost for new tools for the first year. The following years 1-2 new plate models is expected to be released annually, requiring 1-2 new tools each year. Because of this, it has been assumed that 1 new tool will be required every other year, and 2 new tools the other years.

The frequency of which the tools and dies for an eccentric press have to be maintained and sharpened is based on data from the current production. This frequency has been set to every 2000 punches, resulting in 21 tools needing to be sharpened the first year, which increases 7% annually. Based on numbers from the tools workshop in Lund the cost for sharpening dies is 25 000 SEK for smaller dies and 30 000 SEK for larger dies.

The machine maintenance cost for an eccentric press includes costs for spare parts, reparations by external parties, and preventative maintenance, as well as the cost for consumables such as lubricants and oil, where the later counts for a cost of 4 000 SEK annually. Since the annual punching time is relatively low and the machine will never be at maximum capacity, the maintenance cost is assumed to stay the same for the foreseeable future. The reason as to why the machine maintenance is so high the first year, 2024, is that the three current eccentric presses in DC Lund are planned to undergo quite extensive renovations (paintwork, new lubrication pump, new pressure safety valve, and new pressure control) if the decision is made to continue with punching with eccentric presses. This would give DC Lund another 10-15 years with well working machines, which is why another bigger renovation, totaling 396 kSEK, has been added after twelve years, in 2035.

Labor cost is, in addition to the active punching time, based on the required set-up time per batch. Small plates are estimated to require ten minutes for set-up time, whereas medium and large plates are estimated to require fifteen minutes. The number of batches are based on the number of orders handled at DC Lund and orders sent from DC Lund to GCC Lund during 2022, which results in a total set-up time of 716.2 hours per year, which increases 7% annually.

With a static production volume, the key values from the CA are as shown in Table 14, where the total accumulated cost is 40.84 MSEK.

Table 14: Key values from CA for Punching with Eccentric Presses, given in kSEK, with a static production volume.[1]

Cost parameter	2024	2025	2026	…	2035	…	2043	Accumulated after 20 years
Initial investment (machine)	-600	0	0	…	0	…	0	-600
New tools	-12 724	-141	-283	…	-141	…	-141	-16 638
Tool maintenance	-544	-544	-544	…	-544	…	-544	-10 879
Machine maintenance	-1 009	-288	-288	…	-396	…	-288	-6 589
Labor	-304	-304	-304	…	-304	…	-304	-6 088
Total	**-15 182**	**-1 278**	**-1 419**	**…**	**-1 386**	**…**	**-1 278**	**-40 839**

5.4. Additional Parameters

5.4.1. Simplicity of Use

In the comparison of the simplicity of use of each manufacturing method the extent of required training was primarily investigated.

The training that can be required to be able to use these three manufacturing methods is primarily connected to preparing the machine for the next batch as well as cleaning and maintaining the machine. All three methods will most likely require some training and instructions for hole variations, to ensure correct hole variations on each plate. This does, however, depend on how the programs for the AWJC and laser cutter are done. If it is possible to create one cutting program each for all 14 relevant hole variations, the risk for errors such as plates with the wrong number of holes or the holes being placed in the wrong spot decreases.

In order to use and maintain an eccentric press, little training is required. There is some training that must be done regarding how to change the tools correctly and how to know what side of the plate to punch with which tool, since the pattern of the plate can vary between different areas. It is generally enough with peer-to-peer training though, and a new employee can start using the machine independently quite quickly. After an operator is trained there is still a need for continued attentiveness, to make sure that the plates are placed correctly in the punch, that tool changes are carried out correctly, that the tools are not damaged during tool changes and noticing when machine or tools might require cleaning and/or maintenance.

When it comes to AWJC the part of the process that requires the most training is programming the cutting programs that are used, which normally is not done by an operator. For the operators, training can be required on how to do cleaning and maintenance, such as emptying and cleaning the tank and changing nozzles, as well as how to know which

[1] The values shown in the table are rounded to the nearest whole number, which might affect the appearance of the total sum.

parameters are suitable for which situation. These types of trainings are often offered by the machine manufacturer and as soon as one person knows it, it is enough with peer-to-peer training to train others. The time until a new employee can work entirely independently is, however, generally longer than with eccentric presses. After an operator is trained the process is quite simple, with the operator mostly having to pay attention to inserting the correct parameters and noting when cleaning and/or maintenance might be required.

Laser cutting is quite similar to AWJC, with training being required to know which parameters are suitable for what situation as well as how to clean and change filters and change gas tanks. Training is also required to correctly program the cutting programs, which normally is not done by an operator. Initial training is often offered by the machine manufacturer, after which peer-to-peer training is enough to share this knowledge between operators moving forward. After an operator is trained the process is simple, with the operator mostly having to note when cleaning and/or maintenance might be required and using the correct gas depending on the material.

5.4.2. Quality

For determining the quality of the cut edges, factors such as uniformity and straightness of the kerf, surface roughness, burring and any other factors regarding the resulting edge that may affect the product were taken into consideration.

The quality of the cut edges from AWJC can have some problems, especially if cutting parameters that are improperly adapted for the procedure are used. These problems can involve conical kerf resulting in an angled edge if a machine without angle compensation is used, striation marks along the cut, and burrs at the bottom of the cut edge.

For laser cutting, the quality of the cut can also have some problems. This includes burring, striation marks and HAZ (although minimal). However, the extent of these problems, especially burring, requires further testing for conclusive remarks.

Punching with eccentric presses produces good quality cuts, based on results of the current production at DC Lund, provided that the die is sufficiently sharp. If the die is too dull, problems with burring can occur.

Additional problems that could occur with the manufacturing methods are due to handling errors. This could be more prominent when punching with eccentric presses since the process is more reliant on the operator rather than a predetermined program. Due to the amount of different hole configurations (see Figure 2 in section 1.1.2), there is a risk of punching the hole at the wrong position on the plate.

5.4.3. Limitations to Scope of Assortment

It will be possible to make holes in the entire scope of plates that is planned to be handled at DC Lund with all three investigated methods. The larger plates will, for all three methods, require some special handling, in the form of lifting equipment or two operators working together. Additionally, for eccentric presses, a new eccentric press would have to be purchased in order to be able to punch the bigger plates. Furthermore, all three methods are efficient enough to be able to handle all incoming orders, even with a 7% increase in orders per year, over a 20-year period.

5.4.4. Environmental Sustainability

Environmental sustainability and environmental impact can refer to a number of different aspects when it comes to manufacturing methods, such as water and energy consumption, gas and particle emissions, and created waste.

AWJC requires quite a large amount of water in order to function properly. Modern machines do, however, filter and re-use most of the water in the machine, meaning that the environmental impact from water usage is minimal. It is very important that the water that is being pumped out of the machine is filtered properly, since a small percentage of particles from the cut material risks ending up in the outlet water. Therefore, it is important that some sort of external filter and treatment system is installed with an AWJC to minimize the environmental impact from the AWJC.

Regarding power consumption, all three methods use a relatively low amount of energy over the span of a year. With a fiber laser, the amount of energy that is consumed depends greatly on the laser power, which in turn mainly depends on what material is being cut and the thickness of the workpiece. Since all relevant plates are relatively thin, it is deemed that the required power should be quite low. The total annual energy consumption for the three investigated methods will be relatively low as their total running time is relatively short.

5.5. Summary of Analysis

To illustrate the varying costs of the methods annually, a graph with the varying annual costs that include the annual 7% production increase can be seen in Figure 13. The cost for year 2024 is out of bounds due to high initial costs and are not included within the limits to show greater detail to the yearly variations for each method. In year 2025, laser cutting is slightly less expensive than AWJC, with punching with eccentric presses being the most expensive. In year 2043, AWJC is the least expensive and punching with eccentric presses is the most expensive.

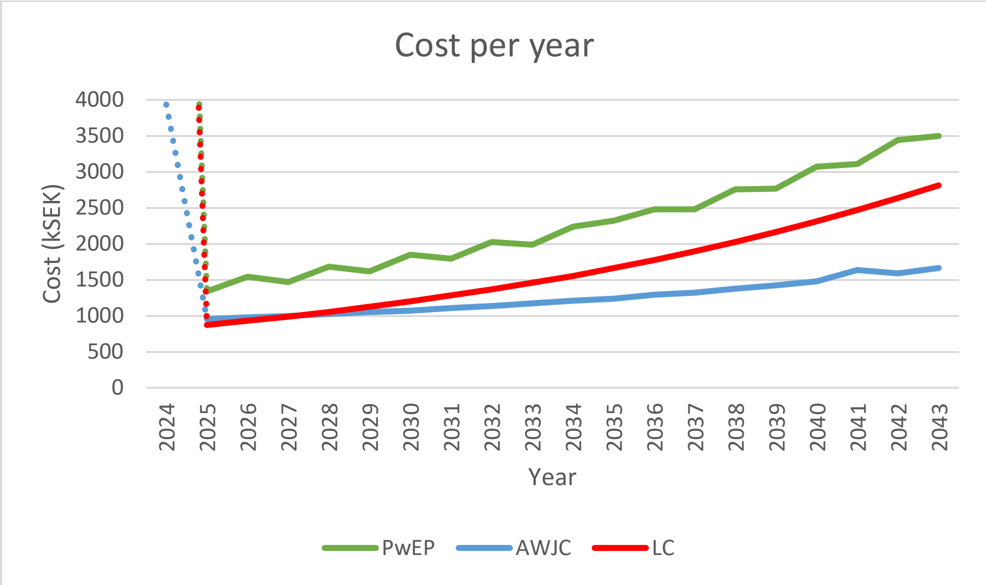

Figure 13: *Annual costs for punching with eccentric presses (PwEP) (green), AWJC (blue) and laser cutting (LC) (red) between 2024-2043, with an annual 7% production increase.*[2]

The accumulated costs with the annual 7% production increase for the manufacturing methods can be seen in Figure 14. In 2024, laser cutting is the most expensive and AWJC is the least expensive. In 2043, punching with eccentric presses is the most expensive and AWJC is the least expensive.

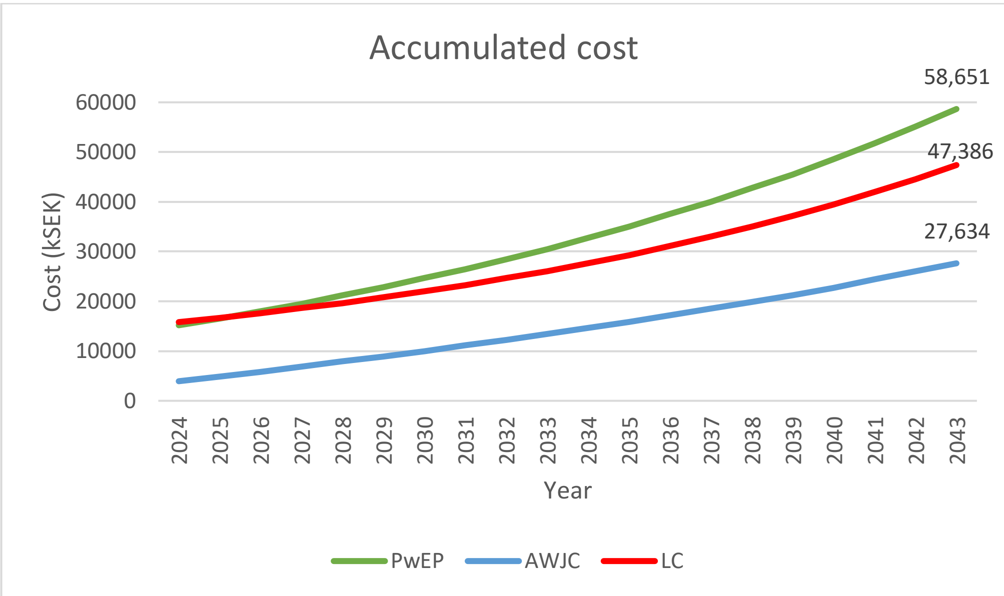

Figure 14: *Accumulated costs for punching with eccentric presses (PwEP) (green), AWJC (blue) and laser cutting (LC) (red) between 2024-2043, with an annual 7% production increase.*

[2] The costs all start at the year 2024, however the cost 2024 exceed the upper bounds and are thereby represented by dotted lines.

A graph with the varying annual costs, where the production volume is static, can be seen in Figure 15. Both in year 2025 and 2043, punching with eccentric presses is the most expensive and laser cutting is slightly less expensive than AWJC.

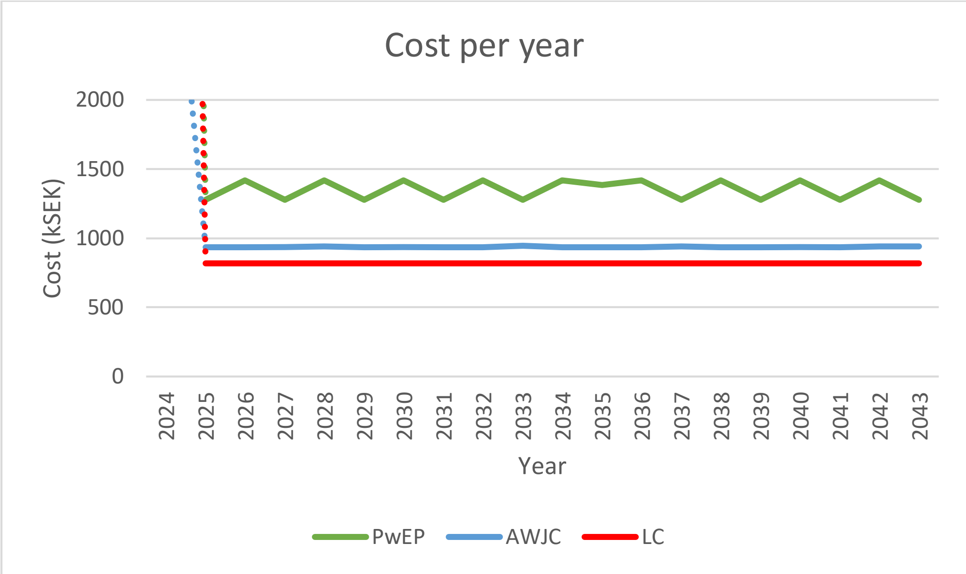

Figure 15: *Annual costs for punching with eccentric presses (PwEP) (green), AWJC (blue) and laser cutting (LC) (red) between 2024-2043, with a static production volume.*[2]

The accumulated costs with a static production volume for the manufacturing methods can be seen in Figure 16. In 2024, laser cutting is the most expensive and AWJC is the least expensive. In 2043, punching with eccentric presses is the most expensive and AWJC is the least expensive.

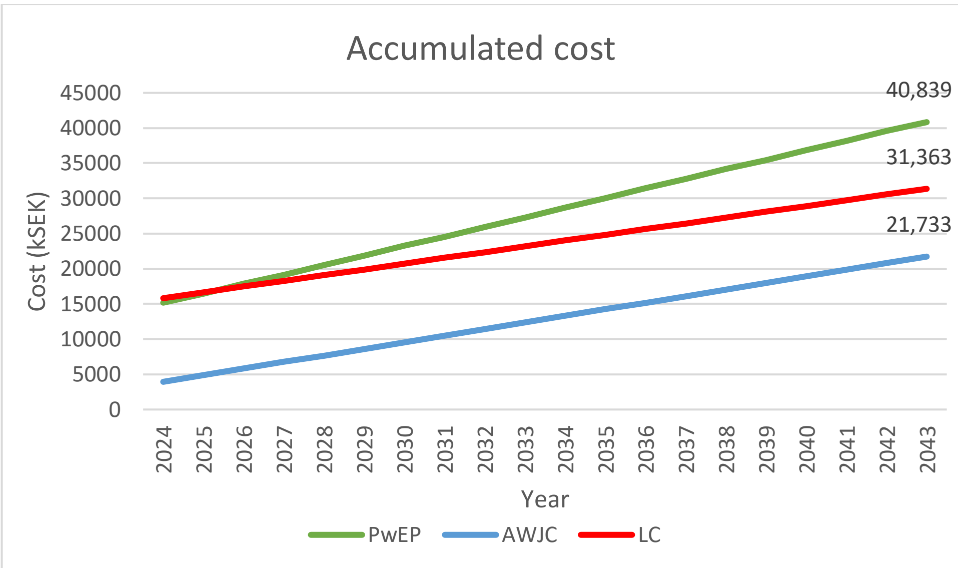

Figure 16: *Accumulated costs for punching with eccentric presses (PwEP) (green), AWJC (blue) and laser cutting (LC) (red) between 2024-2043.*

[2] The costs all start at the year 2024, however the cost 2024 exceed the upper bounds and are thereby represented by dotted lines.

A breakdown of fixed and variable costs accumulated between 2024-2043, both with a 7% annual production increase and a static production volume, are shown in Figure 17 and Figure 18, respectively. Fixed costs include initial investment for all machines as well as costs of new tools and machine maintenance for punching with eccentric presses and cost of machine maintenance for laser cutting. Variable costs include labor for all methods as well as cost of tool maintenance for punching with eccentric presses, costs of consumables (garnet), maintenance, and tools for AWJC, and cost of consumables (assist gas) for laser cutting.

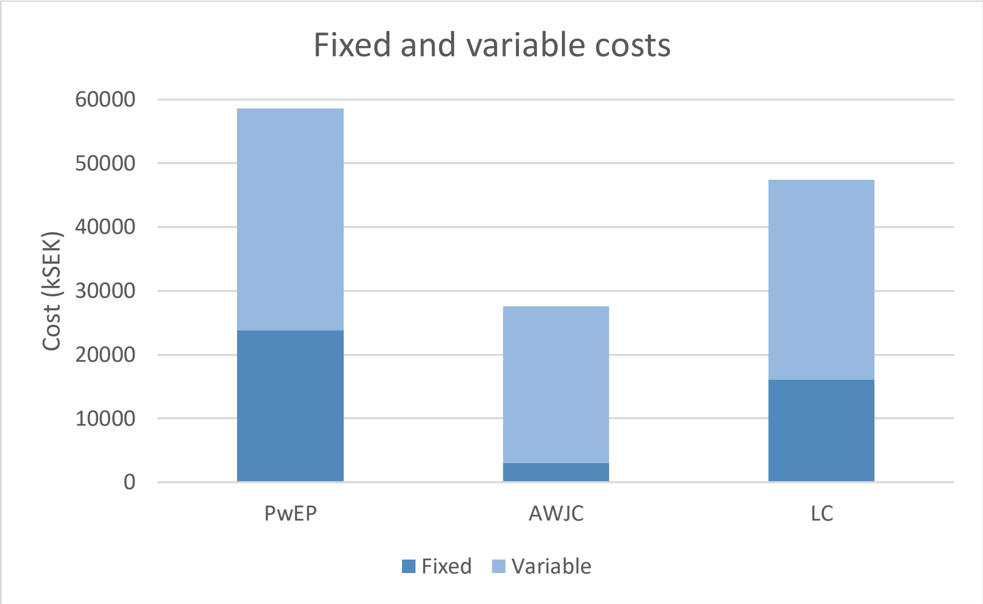

Figure 17: *Fixed and variable costs for punching with eccentric presses (PwEP), AWJC, and laser cutting (LC), accumulated between 2024-2043, with a 7% annual production increase.*

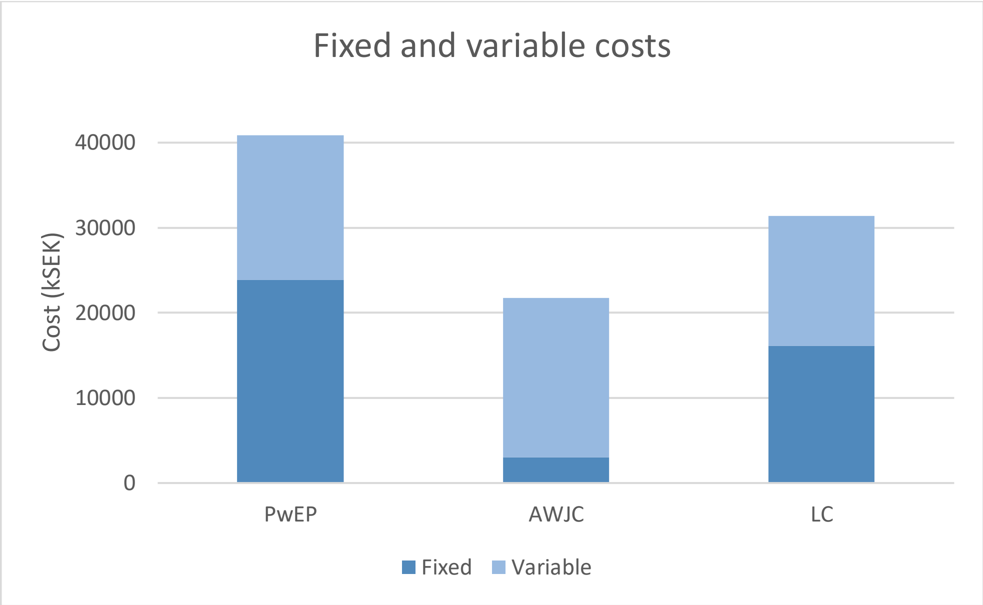

Figure 18: *Fixed and variable costs for punching with eccentric presses (PwEP), AWJC, and laser cutting (LC), accumulated between 2024-2043, with a static production volume.*

A breakdown in the form of pie charts of the contribution of the different cost parameters to the accumulated cost for each manufacturing method, both with a 7% annual production increase and with a static production volume, can be seen in Appendix A.

A summary of the results for each investigated parameter can be viewed in Table 15. Each parameter was scored on a scale of 1-5 based on the analysis above, where 5 is deemed best. The parameters were prioritized based on internal valuing at Alfa Laval and given a score weight on a scale of 1-5, with 5 being the most important, followed by a weighted score for each method based on the previous values.

Table 15: Scored and weighted parameter results for the manufacturing methods.

		Score			Score weight	Weighted score		
	Parameter	AWJC	Laser cutting	Punching		AWJC	Laser cutting	Punching
Efficiency	*Set-up and tool change time*	4	4	2	4	3,2	3,2	1,6
	Post-processing time	2	4	4	4	1,6	3,2	3,2
	Additional lead-time	3	5	2	4	2,4	4	1,6
Work Environment	*Safety for the operators*	2	4	2	5	2	4	2
	Impact on cleanliness in the workspace	2	5	5	2	0,8	2	2
Cost	*Initial investment (machine)*	4	1	5	4	3,2	0,8	4
	Cost of consumables	4	2	5	4	3,2	1,6	4
	Cost of maintenance (tools and machine)	2	5	2	4	1,6	4	1,6
	Tool cost	4	4	1	4	3,2	3,2	0,8
	Labor cost	2	3	2	4	1,6	2,4	1,6
Additional Parameters	*Simplicity of use*	3	3	4	3	1,8	1,8	2,4
	Quality	2	3	4	5	2	3	4
	Limitations to scope of assortment	5	5	3	4	4	4	2,4
	Environmental sustainability	4	4	4	5	4	4	4
	SUM	**43**	**52**	**45**	**56**	**34,6**	**41,2**	**35,2**

Out of a maximum possible score of 56, laser cutting ranked highest with a weighted score of 41.2. This was followed by punching (with eccentric press) with a weighted score of 35.2, and AWJC which ranked last with a weighted score of 34.6.

6. Discussion

For each of the different manufacturing methods, there are some additional costs that can arise that require further investigation to identify the extent of the costs. They have for this reason not been included in the CA. Cost related to the electrical consumption is one example of this, as this would be dependent on the specific choice of machine and the company's electricity contract.

Based on the compilation and scored results in Table 15, the manufacturing method that looks the most promising is laser cutting, which scored the highest. Laser cutting scored well on many highly prioritized parameters such as efficiency, safety for the operators, and maintenance cost, despite the high cost of investment and consumable cost (for assist gas). An important aspect to note is that more testing is required to ensure that a sufficient quality can be achieved for the products with this method. Some of the previous tests suggests that high quality cuts can be achieved, whereas some tests have not achieved sufficient results. Testing that provides consistently good results is required before moving forward with laser cutting as the main production method.

For laser cutting, the calculated cost for consumables could also greatly differ from a real implementation, as the assist gas consumption, and thereby the cost for the gas, is dependent on what further testing suggests is an optimal cutting speed, gas flow and what gas provider is used. A relatively low cutting speed was used for calculation of the gas consumption, which consequently causes a higher gas consumption. The actual gas consumption and cost per cubic meter could potentially be much lower and thereby decrease the total costs significantly. Since the cost of assist gases is one of the biggest cost drivers it could be advantageous to try to calibrate the machine to try to keep the gas consumption as low as possible, while still maintaining a high level of quality.

Additionally, even though modern laser cutters are often encapsulated to keep potentially hazardous gases and vapors away from the surrounding area and equipped with air filters to catch any polluting particles, it could still be necessary to adapt the ventilation system of the building. There might be a need for a stronger ventilation system, extra ventilation drums or special outlets to make certain that the exhaust from the laser cutter is dealt with correctly. This could entail an added cost to the building plans of the new DC Lund. An additional cost for laser cutting that is not included in the CA is the cost of creating the cutting programs for each plate type.

Despite the lowest calculated total cost over the span of 20 years, both with the expected 7% annual production increase and with a static production volume, AWJC scored the lowest in the analysis. While it scored well on multiple cost parameters that are of high importance, it also scored low on other high importance parameters such as safety for the operators and quality. A big contributor to the poor score in safety for the operators is due to the high level of noise pollution as well as the ergonomics involved in handling medium and large plates. The quality of cut is based on results in the production with an AWJC at GCC Lund, where many plates require deburring. Today, this is done by an external company for the plates which are cut using the AWJC in GCC Lund. The need to deburr plates adds additional lead times and costs to the production, either from outsourcing or from investing in deburring equipment to deburr in-house.

An important aspect that has been noted from the machine in GCC Lund today is the levels of nickel in the outlet water. If AWJC were to be proposed as the solution to move forward with, it would be necessary to install a separate water treatment plant to filter the output water more thoroughly. The method also requires frequent maintenance, which stands for a large portion of the method's costs, that would cause undesired downtime to conduct.

The washing and drying of the plates after being cut will add another cost to AWJC which is not included in the CA. This can either be done by sending the plates to an external company, which is done today by GCC Lund, or by doing it in-house, which is done by SC Greenwood. Outsourcing the washing of the plates would lead to more undesirable lead-times, however, doing this in-house would require additional space and equipment. If done directly in the production, which is assumed in the CA, the plates would need to be hosed off directly after the cutting procedure to ease the removal of abrasive particles, and an area for drying the plates would be required. More extensive washing equipment could be required depending on the level of importance that no particles are present on the plate for the application. A fan may also be required to speed up the drying process.

Additionally, to keep potential dust and moisture from the AWJC separate from the rest of the manufacturing processes it could be advisable to isolate the machine by surrounding it with walls. This would also reduce the level of noise pollution to the surrounding areas; however, it would also entail an added cost and potential changes to the building plans of the new DC Lund. An additional cost for AWJC is not included in the CA is the cost of creating the cutting programs for each plate type.

Punching with eccentric presses scored only slightly higher than AWJC, and still lower than laser cutting. Punching scored very well on a few parameters, such as quality and initial investment, but ultimately the low score on some highly prioritized parameters gave a lower total score. This includes a poor score on set-up and tool change time and safety for the operators. This is largely related to the need to continuously change tools for every new product type, which also further contribute to a high labor cost. The mechanical process also causes a lot of tool wear that needs regular up-keep, which involves costs to maintain and long lead-times of up to three weeks.

A cost that is difficult to calculate but that should be taken into consideration is the cost for storing all the tools which are needed. These tools are typically stored in pallet racks, taking up a substantial amount of space that could otherwise be utilized for other parts of the production. Furthermore, there is a cost connected to having to transport these tools to and from the punches, taking up time which could otherwise be used for more directly value creating tasks.

A consequence of continuing with punching with eccentric presses is a potentially increased strain on the tool workshop and maintenance department. With 21 tools requiring maintenance the first year, and 78 tools requiring maintenance in 2043, it may be a prerequisite that these departments are expanded to be able to handle this big influx of incoming work. The cost for new tools also stands out for continuing with punching with eccentric presses, especially in the first year. One way to avoid such a large cost at one time would be to gradually procure the tools that are needed to meet the entire scope of plates. This would mean that DC Lund would have to order plates from GCC Lund for a longer time, which of course comes with its own costs and remaining longer lead times, but that would spread out this large investment over a longer time. An important side note is that the amount of required new tools is an estimation and could potentially be more than the figures used in this report, as some plate varieties may have been missed and some may require more than one tool set.

Regarding the physical space that the different methods would require in the production area, there are a few factors that play a role. For laser cutting, the only factor is the machine itself, the size of which varies greatly between manufacturers. For AWJC, the machine itself, which is generally smaller than a laser cutter, is one factor, and the drying racks that might be used is one factor. How much space the latter requires is difficult to determine, since it depends greatly on how many plates there is a need for drying at the same time. When it comes to punching with eccentric presses, the presses themselves occupy comparatively little space, approximately 1.5 square meters per press. Instead, the tools stored in pallet racks are the bigger factor. With DC Lund needing approximately 110-130 tools, and 24-27 tools can be stored in one rack, this means that 4-5 full pallet racks, occupying approximately 40-50 square meters, would be required to store the tools.

Furthermore, an additional manufacturing method that has not been extensively studied in this report is CNC-punching, as was mentioned by the external source for punching with eccentric presses field study. The method was not studied in the report due to limited knowledge and came to our knowledge late in the conduction of the study. However, if the current tools used for punching with eccentric presses can be repurposed with a machine of this sort, it could potentially be another viable and relatively flexible method.

When evaluating the results from this report, it is important to note that using order data from more than 2022 would give more accurate results. Additionally, the field study is based on input from different individuals. Even though the individuals were deemed to have a high knowledge in the questioned area, and multiple people were included to reduce the occurrence of subjective input, this occurrence may not be completely eliminated.

7. Conclusions

To conclude this study, laser cutting is deemed to be the manufacturing method studied in this report that is the most promising to best fulfill the needs of the production. If sufficient quality is consistently achieved with further testing, the method would allow a more flexible production with shorter lead times and high level of safety. Additionally, through optimization of cutting parameters, cost of consumables could be significantly reduced and result in a lower total cost.

AWJC is presented as the most inexpensive option, however there are additional factors not included in the CA that can contribute to higher costs. If the problem areas with this method can be minimized to a sufficient level, the method could be of interest to implement in the production, as it would allow for a flexible production. This includes enabling better ergonomic practices, decreased noise pollution, decreased maintenance and post-processing needs, and higher quality cuts.

The current production uses punching with eccentric presses, which is deemed to be the most expensive and least flexible option to continue with long-term. The need for a large supply of unique tool sets result in lower flexibility, high expenses and long lead times and is therefore not recommended as a long-term solution.

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Appendix A

Share of cost parameters with a 7% annual production increase:

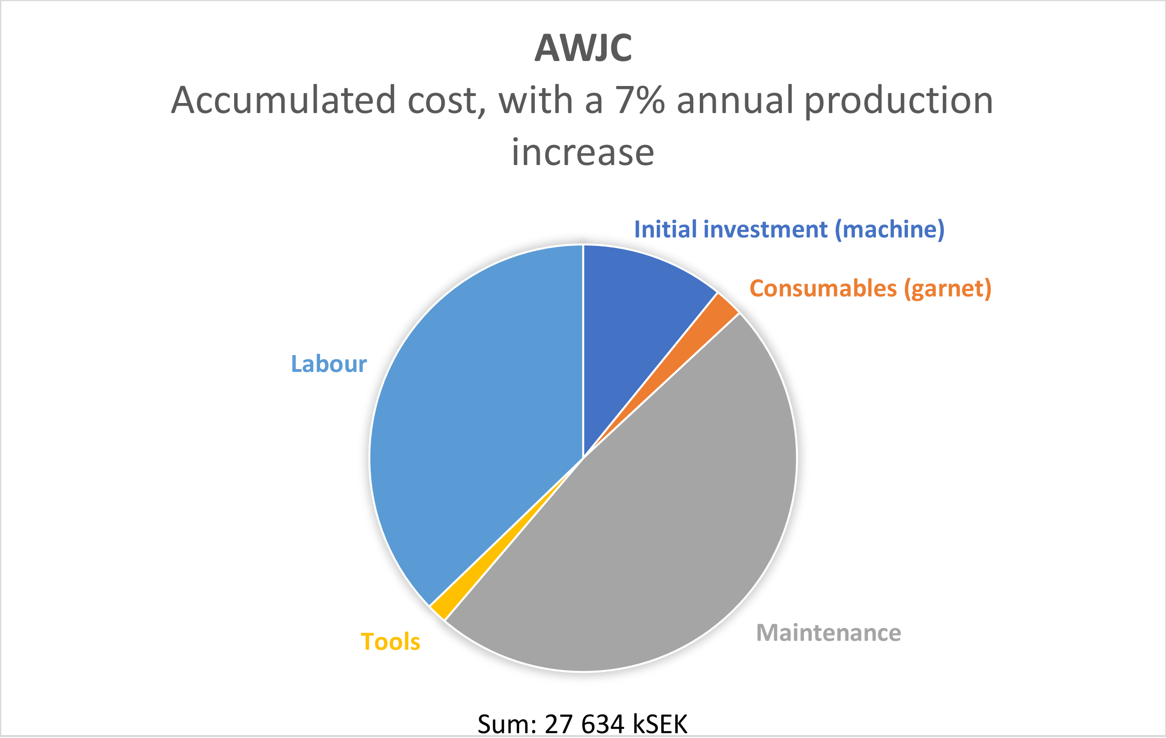

Figure A1: *Cost parameter share with a 7% annual production increase for AWJC.*

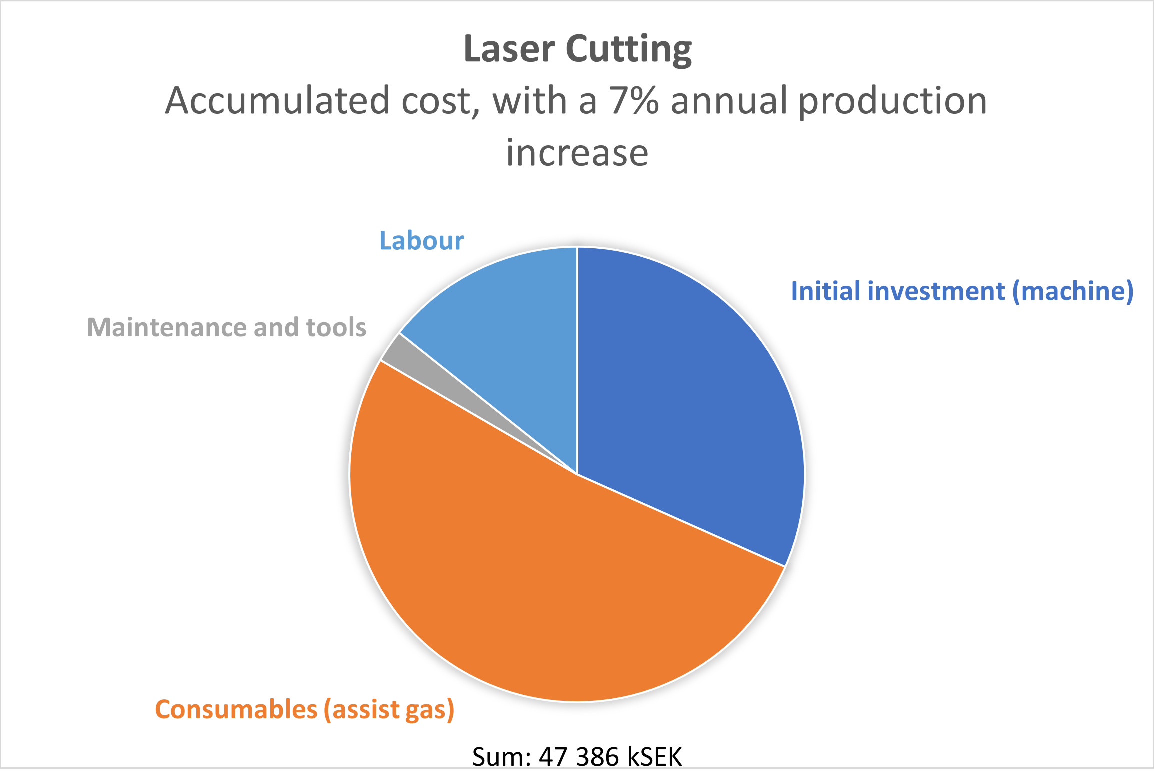

Figure A2: *Cost parameter share with a 7% annual production increase for laser cutting.*

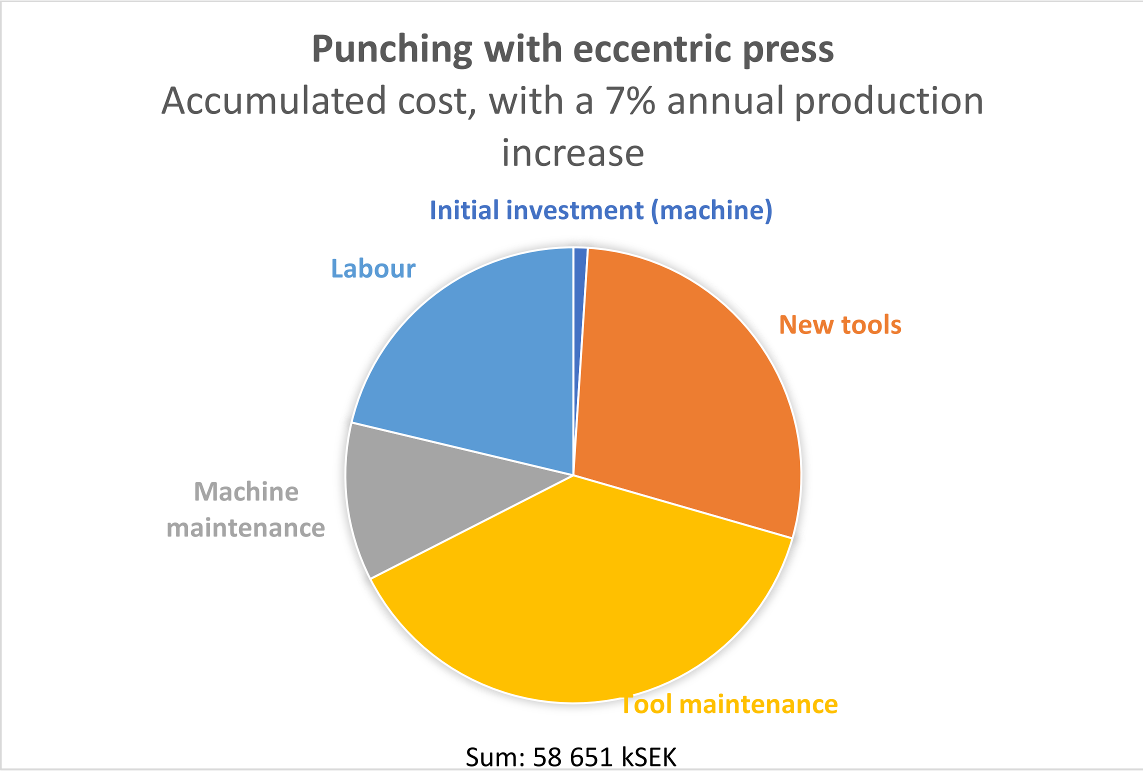

Figure A3: *Cost parameter share with a 7% annual production increase for punching with eccentric presses.*

Share of cost parameters with a static production volume:

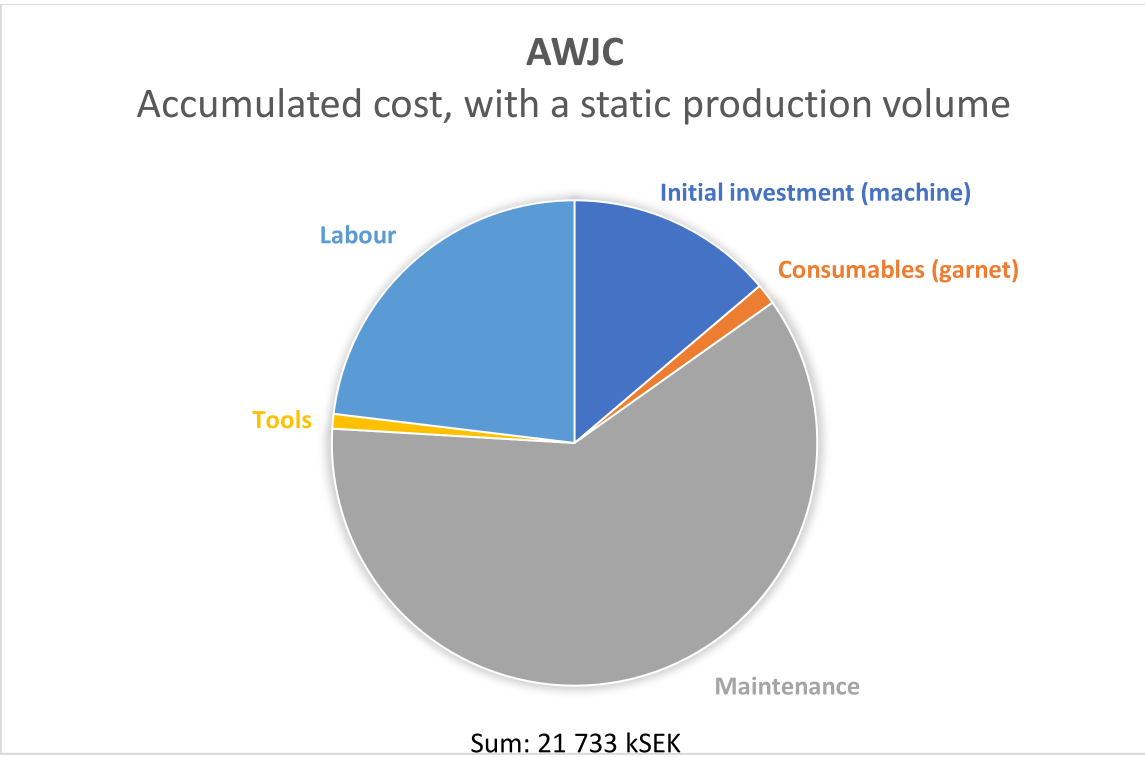

Figure A4: *Cost parameter share with static production volume for AWJC.*

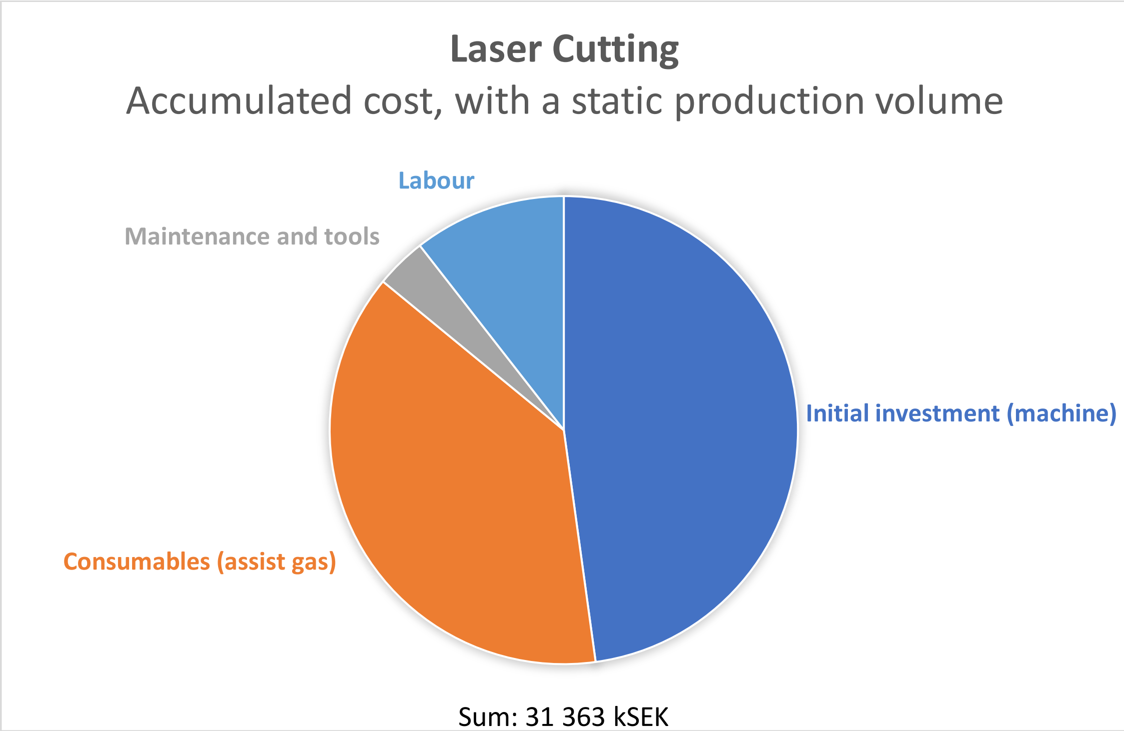

Figure A5: *Cost parameter share with static production volume for laser cutting.*

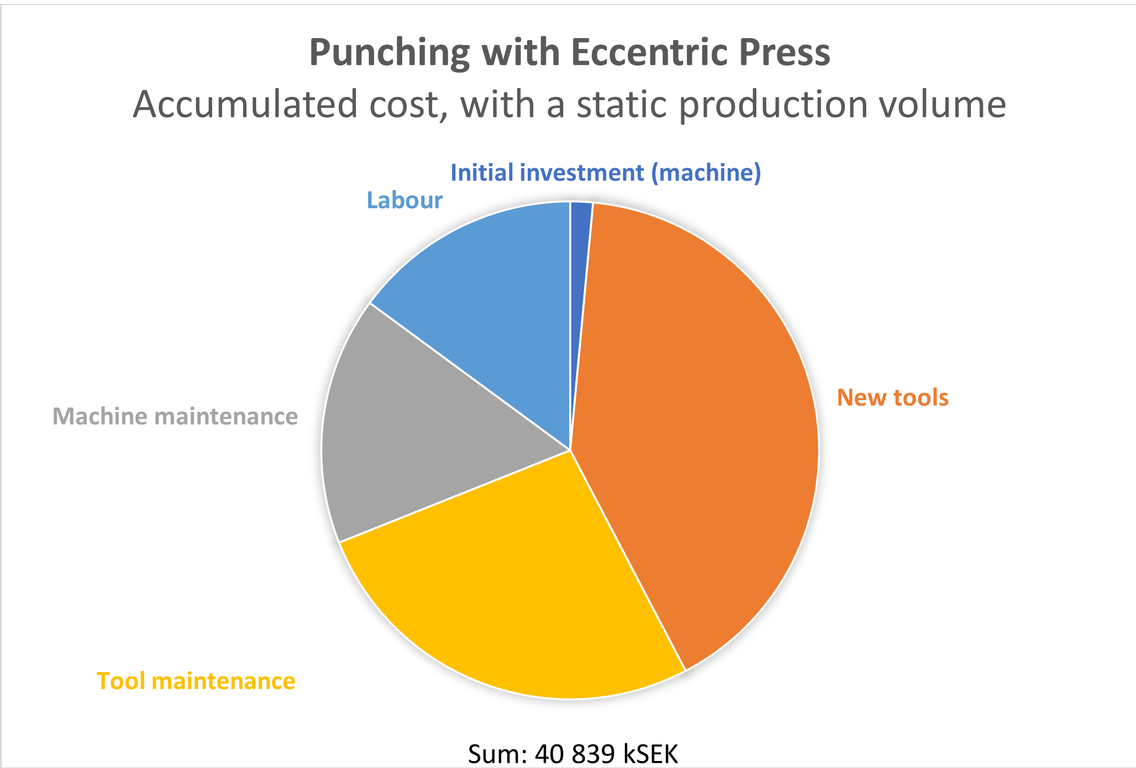

Figure A6: *Cost parameter share with static production volume for punching with eccentric presses.*