TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Mechanical and Industrial Engineering

TECHNO-ECONOMICAL COMPARISON OF CUTTING METAL SHEETS WITH PLASMA, OXY-FUEL AND LASER TECHNOLOGIES

METALLLEHTEDE LÕIKAMISE TEHNO-MAJANDUSLIK VÕRLDLUS PLASMA-, GAASI JA LASERTEHNOLOOGIATEGA

MASTER THESIS

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Tallinn 2024

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1 INTRODUCTION

In the evolving landscape of manufacturing industries, the creation and preparation of parts play a pivotal role in enhancing production efficiency and product quality. With technological advancements, traditional metal cutting methods such as plasma and oxy-fuel are now contending with modern laser cutting technologies, which have grown significantly in popularity due to their decreasing costs and improved capabilitiesp.[1][2] This thesis aims to provide a comprehensive techno-economic comparison of these three cutting technologies—plasma, oxy-fuel, and laser—specifically focusing on their application within the context of TerasToorik AS, a company specializing in the cutting of metal sheets.

The relevance of this study is underscored by the manufacturing sector's continuous pursuit of optimization in cost and operational efficiency. Metal cutting technologies form the backbone of the industry, influencing both the initial cost of production and the quality of the final product. As such, selecting the most efficient and cost-effective cutting technology is crucial. The advancements in laser technology, alongside the robustness of traditional methods such as plasma and oxy-fuel, necessitate an updated evaluation to determine the most viable option in contemporary manufacturing environments.

The primary objective of this thesis is to compare the technological and economic aspects of laser, plasma, and oxy-fuel cutting methods employed by TerasToorik AS. This comparison aims to identify the optimal cutting technology that balances operational efficiency with cost-effectiveness. The outcomes of this research will provide TerasToorik AS with data-driven insights into selecting appropriate cutting technologies that could potentially revolutionize their production processes and economic outcomes.

To achieve these objectives, the research methodology will include the selection of appropriate cutting machines, defining comparative parameters for each technology, and collecting relevant data from TerasToorik AS. This will be followed by a detailed techno-economic analysis of the gathered data to evaluate each technology's performance and cost implications.

TerasToorik AS serves as the practical framework for this study. The company's operations in cutting metal sheets with all three technologies provide a unique opportunity to conduct an in-depth analysis of current industry practices and their economic impacts. Insights gained from TerasToorik AS will not only benefit the company but also contribute to broader academic and industrial understandings of metal cutting technologies.

This thesis will therefore explore both the strategic implications of technology selection and its operational impact, providing a nuanced perspective on metal cutting technologies in the modern manufacturing milieu.

2 Background

In the evolving landscape of manufacturing technologies, the sheet metal cutting industry represents a focal point of innovation and precision. Central to this sector's advancement are three methodologies—laser cutting, plasma cutting, and oxyfuel cutting—each pivotal for their distinct contributions to manufacturing excellence. This chapter seeks to lay the groundwork for a comprehensive analysis of these cutting technologies by establishing a dual focus: the industry context and the involvement of a key entity within this domain, TerasToorik AS.

The narrative unfolds in two sections, with the initial part providing a background on TerasToorik AS. This exploration covers the company's operational ethos, market positioning, and contributions to the sheet metal cutting field. The account extends beyond an organizational overview, reflecting on the industry's broader challenges and achievements, thereby setting a real-world context for the technologies under discussion.

Following this, attention shifts to a broader examination of the sheet metal cutting industry. Without delving into the specifics of laser, plasma, and oxyfuel cutting technologies—which are reserved for detailed exploration in subsequent chapters—this segment offers an overview of the industry's technological landscape. It aims to frame the discussion within the realms of academic inquiry, highlighting the importance of these technologies in pushing the boundaries of what is possible in sheet metal manufacturing.

Thus, this chapter serves as the foundation for a nuanced comparison of cutting technologies in later discussions. By intertwining industry insights with a scholarly approach, it sets the stage for an in-depth examination of the methodologies that have become indispensable to modern manufacturing processes. The intention is to provide a narrative that is not only informative but also indicative of the industry's trajectory toward innovation and efficiency.

2.1 Company and author’s background

TerasToorik AS, an Estonian-based enterprise, excels in the realm of metal cutting, offering a wide array of services including, but not limited to, plasma cutting, oxy-fuel, and laser cutting. With the capacity to handle large-volume orders, the company distinguishes itself by providing additional high-quality metalworking services such as bevelling, bending, and shot peening. Boasting a monthly cutting work volume exceeding 450 tons and having established its foundation in 2004, TerasToorik AS has risen to become a successful company within Estonia's steel industry, distinguished by its comprehensive service offerings and significant contribution to the sector.[3]

The choice of TerasToorik AS as the focal point of this thesis is predicated on a confluence of professional and academic motivations. Firstly, the author's tenure at TerasToorik AS as a production and process engineer affords an insider's perspective on the operational dynamics and technological intricacies inherent to the company's cutting processes. This position enables unparalleled access to empirical data and firsthand observations, enriching the thesis with nuanced insights into the practical application of plasma, oxy-fuel, and laser-cutting technologies within the industry.

Furthermore, TerasToorik AS embodies the ideal case study for this thesis due to its comprehensive utilization of the trio of cutting technologies under scrutiny. The presence of plasma, oxy-fuel, and laser-cutting technologies within a single organization provides a unique opportunity to conduct a comparative analysis of cost-effectiveness, efficiency, and quality across these methodologies. Such an analysis is instrumental in understanding the strategic advantages and limitations of each technology, thereby contributing to a more nuanced discussion on their applicability and sustainability in the metal-cutting industry.

As mentioned above TerasToorik AS is equipped with advanced machinery enabling a wide spectrum of metal cutting techniques, notably plasma cutting, oxy-fuel cutting, and laser cutting, each offering distinct advantages in terms of precision, efficiency, and material compatibility.[3]

Plasma cutting technology at TerasToorik AS facilitates cutting through metal up to 50mm in thickness, showcasing the method's adaptability to various industrial needs with high speed and precision. This technique is pivotal for projects requiring intricate patterns and rapid production cycles.[3]

Oxy-fuel cutting, employed for materials surpassing plasma cutting's thickness limit, can efficiently slice through steel up to 300mm thick. This capacity underscores the company’s ability to handle robust materials and projects demanding substantial material removal.[3]

Laser-cutting machines further augment the company's precision-cutting services, with the capability to process metals up to 50mm thick. This method is celebrated for its accuracy and the quality of the finish, essential for detailed work and high aesthetic standards.

Beyond cutting, TerasToorik AS extends its expertise to metal bevelling, bending, and shot peening, offering comprehensive post-processing services that enhance product quality and application. These capabilities demonstrate TerasToorik AS's commitment to delivering end-to-end solutions, from precise cutting to specialized finishing techniques, affirming its status as a successful entity in the steel industry.[3]

2.2 Sheet metal cutting industry

The sheet metal cutting industry is the first step of most production such as construction, automotive, aerospace, and more. One of the key characteristics is the ability to work with a wide range of materials. The selection of material is contingent upon precise application criteria, encompassing factors such as mechanical strength, resistance to corrosion, and electrical conductivity. This inherent flexibility enables the sheet metal industry to effectively address a myriad of requirements spanning across various industrial sectors.

This versatility is crucial not only in meeting the specific demands of each project but also in adapting to evolving technological advancements and engineering practices. For instance, in the construction industry, the choice of sheet metal can impact the longevity and sustainability of structures. In the automotive sector, it influences vehicle efficiency, safety, and performance. Meanwhile, in aerospace, the emphasis is on minimizing weight while maximizing strength and resistance to extreme conditions.

Moreover, the industry's capacity to innovate in cutting techniques, such as laser cutting, waterjet cutting, and plasma cutting, further expands its capability to provide precise and efficient solutions. These advanced methods allow for intricate designs and tight tolerances, opening up new possibilities in product development and manufacturing.

Environmental considerations also play a significant role in material selection and cutting practices. The industry is increasingly adopting eco-friendly approaches, such as recycling scrap metal and using cutting methods that minimize waste and energy consumption. This shift not only addresses environmental concerns but also contributes to cost efficiency and compliance with regulatory standards.

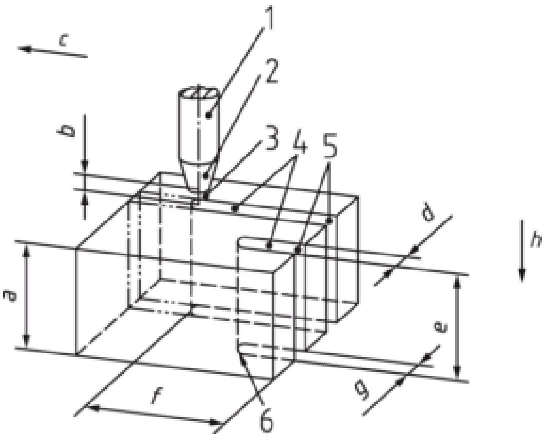
In essence, the sheet metal cutting industry's ability to work with a diverse range of materials, coupled with its ongoing technological and environmental innovations, makes it a cornerstone in the production chain of many sectors. Its adaptability and precision in meeting specific industrial needs underscore its importance in the global manufacturing landscape.

2.2.1 Tools and techniques

The sheet metal industry depends on a diverse array of specialized tools and equipment, including but not limited to shears, press brakes, rollers, and CNC (Computer Numerical Control) machines. These indispensable instruments play a vital role in the intricate sheet metal fabrication process. Their operation is entrusted to highly skilled technicians who deeply understand the complexities of manipulating sheet metal.

One of the most important methods of cutting metal sheets is thermal cutting. The most widely used are the following types of thermal cutting: plasma, oxygen, and laser.

All types of thermal cutting have the same key terms as in Figure 1. Terms 1, 2, and 3 relate to the machine. The cutting head is the metal tube within which the reaction of gasses with the cutting technology happens. The nozzle works as a focus point for a beam, flame, or arc (depending on the type of thermal cutting). This will generate kerf (term 4, figure 1). Kerf is the diameter of a beam, flame, or arc that engineers have to take into consideration when they plan to cut. Starting and ending points will be referred to as lead-in and lead-out in the following work.



Key

1	torch/cutting head
2	nozzle
3	beam/flame/arc
4	kerf
5	start of cut
6	end of cut

a	work piece thickness
b	nozzle distance
c	advance direction
d	top kerf width
e	cut thickness
f	length of cut
g	bottom kerf width
h	cutting direction

Figure 1. Terms related to the cutting process of the workpiece

Source ISO 9013:2017 [4]

2.2.2 Nesting

The main goal of a manufacturing company that deals with sheet metal cutting using thermal cutting is material waste reduction. To get maximum profit companies must use the maximum area of the metal sheet. This leads us to the following: "To reduce waste material, parts are assigned in sheet metal as many as possible. This assignment operation is called nesting. " [5] Nesting is an essential tool in the modern sheet metal cutting industry. This operation is usually done by CAM (Computer Aided Manufacturing) programs. Here, it is important to mention that In the realm of CAM system-based part processing design, the programmer can engage in a simulation of the part processing within a virtual environment. This simulation allows for the meticulous examination of any potential conflicts among machine components and any undesirable interactions with the part itself, ensuring a collision-free and gouge-free process [6, p. 3, point 2].

3 Types of cutting technologies

In the dynamic realm of the sheet metal cutting industry, the evolution of cutting technologies has been pivotal in addressing diverse manufacturing challenges. Plasma, oxy-fuel, and laser cutting each represent a cornerstone of this technological advancement, offering unique capabilities that enhance efficiency and precision. This chapter is dedicated to a detailed examination of these technologies, emphasizing their operational characteristics, comparative benefits, and the spectrum of applications they enable within the manufacturing sector.

The discourse begins with an overview of plasma cutting, highlighting its role as a versatile and swift method suitable for a wide array of materials. This section focuses on the operational advantages of plasma cutting and its application breadth, aiming to underscore its effectiveness in contemporary manufacturing settings without engaging in complex technical details.

The narrative then transitions to oxy-fuel cutting, a method renowned for its proficiency in cutting through thick steel. By outlining the operational methodology and specific use cases of oxy-fuel cutting, this part of the chapter seeks to illuminate its specialized niche within the industry. The emphasis is on understanding the utility and application areas of oxy-fuel cutting, rather than its historical development or technical intricacies.

Concluding the analysis is a segment on laser cutting technology. This section delves into the high precision and versatility of laser cutting, capable of intricate work across various material types. The discussion is structured to highlight the wide-ranging applications of laser cutting and its transformative impact on manufacturing practices, steering clear of the deep technical mechanics that underpin its operation.

Through a comparative lens, this chapter aims to present a cohesive understanding of plasma, oxy-fuel, and laser cutting technologies, focusing on their operational essence and application diversity. The objective is to equip the reader with a clear perspective on how these technologies differentiate themselves in terms of functionality and suitability for specific manufacturing tasks. This approach facilitates a comprehensive view of the current technological landscape in material processing, emphasizing practical applications and operational advantages without delving into historical context or overly technical details.

3.1 Plasma cutting

As in physics: "A plasma is a quasineutral gas of charged and neutral particles which exhibits collective behavior."[7, p. 3]

For the sheet metal cutting industry, the following definition is used: Plasma Arc Cutting (PAC) constitutes a thermal manufacturing technique employed in the precision severing of metal plates [8]. This method leverages the high-energy ionized gas, known as plasma, to melt metal in a localized area, facilitating a focused and precise cut. The effectiveness of PAC is underscored by its capability to handle metal thicknesses ranging from 5 to 40mm, showcasing its adaptability to various industrial needs[8].

In industrial settings, plasma-cutting technology is heralded for its efficiency and versatility. It not only allows for the rapid and accurate cutting of metals but also presents a cost-efficient alternative to other cutting methods like abrasive water jet or laser cutting. This cost efficiency is derived from both lower initial setup costs and reduced operational expenses, making PAC an attractive option for businesses looking to optimize their manufacturing processes. The high cutting velocity of plasma cutting further enhances productivity compared to other types of thermal cutting.[9]

Moreover, the application of plasma cutting extends beyond the mere severing of materials; it is also instrumental in shaping and forming metal components, thus playing a crucial role in various manufacturing stages. The technology's precision and speed make it an indispensable tool in industries where time and accuracy are of the essence, such as automotive manufacturing, aerospace engineering, and construction. Its ability to efficiently cut through different types of metals, including but not limited to steel, aluminum, and copper, underscores its broad applicability and significance in the modern industrial landscape.

As in Figure 2 plasma acr is generated as follows:

1. The gas gets into the nozzle
2. The electrode initiates the reaction of gas
3. The plasma arc moves to the outer nozzle
4. In the outer nozzle of the plasma arc gets its final shape
5. The cutting sequence starts

Here, it is important to mention that the electrode in this case works as an anode (-) and the working piece as a cathode(+).

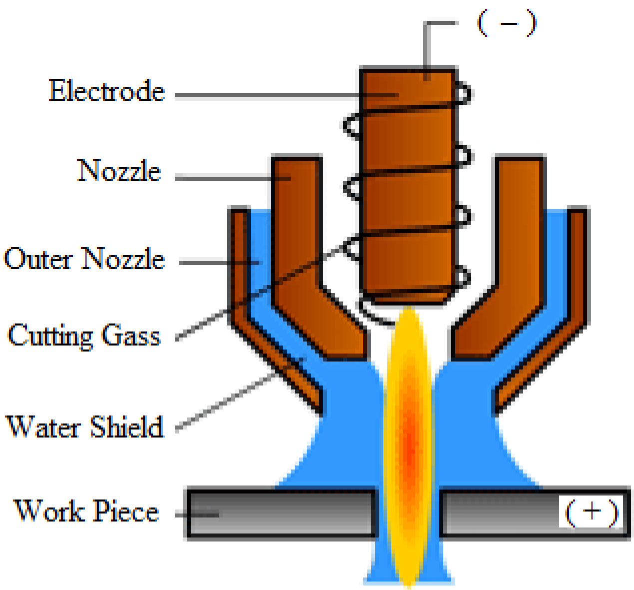


Figure 2. Plasma Arc Cutting mechanism

Source Research Gate [10]

3.2 Oxygen cutting

Oxyacetylene flame cutting stands as a widely adopted industrial technique, crucial for its application across various manufacturing domains. This process fundamentally relies on the rapid oxidation of metal at elevated temperatures to achieve precise cuts on metal sheets with bigger thicknesses usually from 40mm up to 300mm [11]. By harnessing the intense heat generated from the oxyacetylene flame, the metal is quickly brought to its ignition temperature, facilitating a controlled and efficient cutting action. This method's efficacy is particularly noted in its ability to smoothly slice through thick metal sections, making it an invaluable tool in environments where precision and reliability are paramount. The interplay of oxygen and acetylene not only enables a high degree of accuracy but also allows for the handling of a diverse range of metals, thereby broadening its utility in industries such as construction, fabrication, and automotive manufacturing.

The affordability of equipment for oxy-fuel gas cutting plays a significant role in its widespread adoption. This method involves using a cutting torch to elevate the metal's temperature to the point where it begins to emit a red glow, indicating it has reached its kindling temperature [11]. The simplicity of this setup, combined with the low operational costs, makes oxy-fuel cutting an attractive option for both large-scale industrial applications and smaller, more specialized projects. At this juncture, a focused oxygen stream is directed onto the heated metal, causing it to react and form an oxide slag that is expelled, thus forming the cut or kerf. This expulsion of material is what precisely defines the cutting path and allows for the creation of complex shapes and designs with relative ease [11]. This process is influenced by several factors including the size, type, and positioning of the torch tip relative to the metal surface, as well as the rates of oxygen and preheat gas flow and the velocity at which the cutting is performed. Moreover, the underlying chemical reactions, specifically the oxidation of the metal being cut, play a crucial role in determining the dynamics of the cutting process.

3.3 Laser cutting

Laser cutting is an incredibly efficient and precise method that hinges on the use of a potent beam of infrared light, originating from a high-powered laser. This beam is meticulously directed and concentrated onto the surface of the material that is being cut. The process involves the careful use of a lens to focus the laser beam to a fine point on the workpiece, ensuring that the beam's intensity is maximized at the specific point of contact [12].

Once the laser beam is accurately focused, it begins to interact with the material, heating it to extreme temperatures. This intense heat is localized to a very small area, which is crucial for achieving the high precision that laser cutting is known for [12]. The heat is sufficient to melt the material at the point of focus, penetrating through the entire depth of the material, even if it is a thick sheet, thereby creating a cut.

The focus of laser plays a significant role in industrial applications. There are three types of laser focus: negative, positive, and zero. A negative focus means that the focus is located in the bottom of the workpiece. This focus is widely used on thicknesses from 0.5 up to 40mm. The cutting happens quicker, but the edges of the parts are not shiny. In comparison, the positive focus is located higher than the workpiece. The cutting is slower than with negative focus because when the beam reaches the surface of the metal sheet it still has to cut the whole thickness of it. Due to speed and working principle, the surface of the parts is very shiny and has no traces of cutting. The zero focus of the cutting process is situated on the workpiece's surface, which typically exhibits a relatively smooth finish in proximity to the focused cutting area. However, the surface further from the cutting focus, particularly on the lower side, tends to display a rougher appearance [13]. This focus is suitable for smaller thicknesses due to its working principle.

To complement the action of the laser, a pressurized gas jet plays a critical role in the cutting process. This jet is aligned perfectly with the laser beam [Figure 3], ensuring that it works in tandem to remove the molten material from the cut path [12]. The gas jet is not merely a mechanical tool for ejecting the molten material but also serves a chemical function in certain cutting scenarios. A notable example is the cutting of steel, where a jet of pure oxygen is employed. The intense heat from the laser initiates a rapid oxidation process in the steel, a reaction that releases additional heat [14]. This extra heat contributes significantly to the cutting process, enhancing the efficiency and effectiveness with which the laser cuts through the steel.

This intricate interplay between the focused laser beam and the coaxial pressurized gas jet defines the essence of laser cutting, enabling it to perform cuts with unparalleled precision and efficiency[12]. The method is distinguished by its ability to deliver clean, precise cuts across a variety of materials, making it a favored choice in numerous industrial and manufacturing applications.

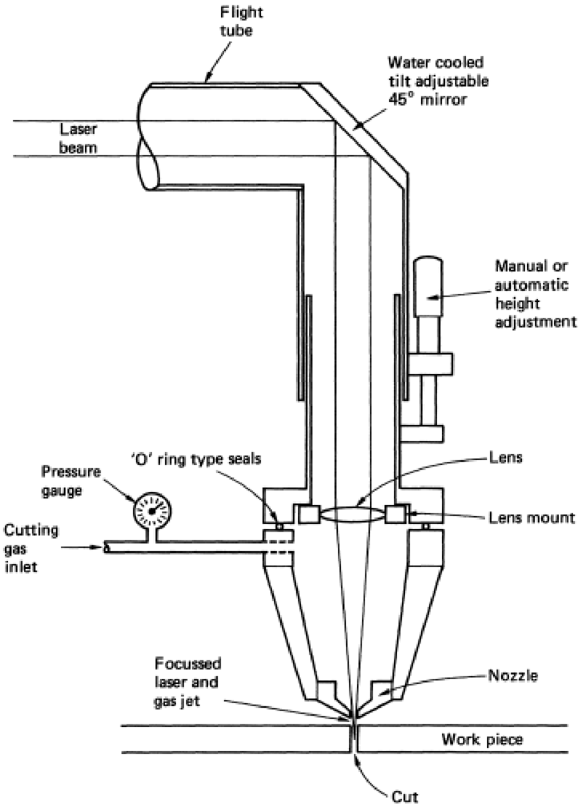


Figure 3. Schematics of laser cutting

Source CO2 Laser Cutting book [15]

4 Techno-economical comparison

In the subsequent chapter, an exploration of the problem statement will be articulated, delineating the pertinent issues within the scope of inquiry. This will be succeeded by an elucidation of the machinery under consideration, encompassing a comprehensive explication of their functionalities, operational mechanisms, and significance within the context of the study. Following this exposition, a meticulous techno-economic analysis will be undertaken, aimed at evaluating the comparative efficacy of various technologies concerning their waste generation patterns and associated economic costs. This analytical endeavor will encompass a thorough examination of the technological landscape, the environmental ramifications of each option, and the corresponding financial expenditures requisite for their implementation and sustenance. Through this multifaceted examination, a nuanced understanding of the interplay between technological feasibility and economic viability will be fostered, thereby facilitating informed decision-making processes.

4.1 Problem statement

This chapter begins by reviewing Previous Research, identifying the achievements and limitations of existing studies to contextualize inquiry. This section not only acknowledges the foundational work of others but also highlights the gaps that the current research seeks to fill, setting the stage for discoveries.

Next, the Hypothesis section introduces a proposed solution to the research question, developed from insights gathered in the review. It details predictions and their reasons, highlighting the importance of this hypothesis in the broader field of study.

Finally, the Methodology details the practical steps that will be taken to test of hypothesis, from data gathering to analysis. This section bridges the gap between theoretical and empirical investigation, outlining the methods that will bring clarity to the hypotheses.

4.1.2 Previous researches

This subchapter on Previous Research provides an overview of significant studies comparing various material-cutting technologies. It focuses on two key aspects: the techno-economic aspects of using laser, plasma, and oxygen-cutting methods, and the impact of these technologies on the quality of structural steel cuts. The first study offers insights into cost-effectiveness and efficiency, while the second evaluates the quality of the cuts produced. Together, these studies contribute to a broader understanding of the strengths and limitations of each cutting technology, laying the groundwork for further exploration in the field.

In the landmark 2012 study titled "TECHNO-ECONOMICAL COMPARISON OF CUTTING MATERIAL BY LASER, PLASMA, AND OXYGEN," a dedicated team of researchers embarked on a comprehensive examination of the economic and technological efficiencies of various metal sheet-cutting technologies. The core objective of this research was to ascertain the most cost-effective and efficient method for cutting S355J0, a commonly used structural steel, by comparing laser, plasma, and oxygen cutting techniques across three distinct material thicknesses: 10mm, 15mm, and 20mm.[16]

Through a meticulous analysis of the data collected, the study revealed a significant advantage in favor of plasma cutting. Not only did plasma cutting yield a higher number of parts per unit of time, but it also emerged as the most economically viable option among the three tested methods, particularly when considering the cost-to-output ratio. The superiority of plasma cutting in terms of both productivity and cost-effectiveness positions it as a compelling choice for industries engaged in the cutting of metal sheets.[16]

It is critical to acknowledge, as highlighted by the researchers, that the scope of the study was intentionally focused. The comparison was limited to three specific thicknesses of a single steel type, S355J0, thereby providing a concentrated view of the performance capabilities of the cutting technologies under consideration. Furthermore, the parameters of the study included the use of a 4 kW laser [17], a detail that underscores the technological context within which the findings were generated. This limitation is an important consideration for the application of the study's conclusions, indicating that the results are most relevant to scenarios that closely mirror the experimental conditions, including the material type, thickness, and laser power utilized.[16]

In the insightful research titled “Comparison of Laser Beam, Oxygen, and Plasma Arc Cutting Methods in Terms of Their Advantages and Disadvantages in Cutting Structural Steels,” a dedicated team of researchers embarked on an examination to delineate the cutting efficacy across three prevalent technologies. Utilizing S235JR as the material of choice, this study meticulously explored the outcomes associated with varying material thicknesses, specifically 3mm, 5mm, 6mm, 8mm, and 15mm. A key observation from this research underscores the cost-effectiveness of plasma and oxygen-cutting methods compared to their laser counterparts. However, a critical advantage of laser cutting emerged in terms of the surface finish quality. The researchers highlighted a notable distinction in the degree of inclination or conicity of the cuts, with laser technology achieving nearly zero conicity. This stark contrast underscores the superior precision of laser cutting, despite its higher cost, when compared to the more noticeable inclination observed in cuts made by plasma and oxygen methods. [18]

4.1.3 Hypothesis

Building upon the foundational insights garnered from prior research on material-cutting technologies, this hypothesis posits a forward-thinking proposition: "New 30kW lasers are more cost-effective for cutting metal sheets compared to traditional plasma and oxygen-cutting methods." This assertion is grounded on the evolution of laser technology, particularly the advancements leading to the development of 30kW lasers, which have significantly enhanced cutting capabilities.

The rationale behind this hypothesis emerges from several key observations drawn from existing studies. Firstly, previous investigations primarily focused on lasers with lower power ratings, which, while effective, did not harness the full potential of cutting speed and efficiency that newer, high-powered lasers offer. The introduction of 30kW lasers marks a paradigm shift, promising not only increased cutting speeds but also the ability to process higher volumes of parts within shorter time frames. This leap in productivity could dramatically reduce operational costs, making it a pivotal factor in the cost-effectiveness analysis.

Secondly, the advanced precision of 30kW lasers translates to a reduced need for consumables, such as gases and cutting tools. The efficiency of these lasers is further amplified by their ability to maintain a minimal gap between the metal sheet and the nozzle, which optimizes gas usage and minimizes waste. This aspect is particularly critical when considering the ongoing costs associated with material-cutting operations, where consumables represent a significant portion of the expenses.

Furthermore, the enhanced capabilities of 30kW lasers are expected to result in a lower frequency of consumable replacements. This is due to their refined cutting accuracy and the reduced wear and tear on components, factors that not only contribute to cost savings but also the sustainability of the cutting process by minimizing waste and downtime.

In synthesizing these elements, this hypothesis underscores the potential for 30kW lasers to revolutionize the metal sheet-cutting industry. By offering a solution that is both technologically advanced and economically viable, this research seeks to demonstrate that high-powered lasers can outperform traditional plasma and oxygen-cutting methods, providing a compelling alternative that aligns with the industry's evolving needs and priorities. The subsequent investigation will rigorously test this hypothesis, employing a comprehensive methodology to explore the techno-economic benefits of 30kW laser cutting technology in comparison to established methods.

4.1.4 Methodology

This subchapter delineates the comprehensive methodology adopted to empirically investigate the hypothesis that 30kW lasers present a more cost-effective solution for cutting metal sheets compared to traditional plasma and oxygen-cutting methods. This investigation will specifically focus on three distinct metal sheet thicknesses: 5mm, 25mm, and 50mm. These thicknesses have been strategically chosen to encompass the range of materials frequently encountered in the industry, from the precision-sensitive thin sheets to the power-demanding thick plates.

Selection of Materials and Machines

For each of the selected thicknesses, equivalent grades of structural steel will be utilized across all cutting technologies to ensure consistency in material properties. The cutting technologies to be evaluated include:

- Laser Cutting: Utilizing a state-of-the-art 30kW laser machine, known for its precision and speed.
- Plasma Cutting: Employing a high-definition plasma cutting system, widely recognized for its efficiency in medium to thick plate cutting.
- Oxygen Cutting: Using a traditional oxygen-acetylene torch setup, a method traditionally favored for thick material cutting due to its cost-effectiveness.

Comparative Parameters

The evaluation will be structured around a set of key parameters to ensure a comprehensive techno-economic comparison:

- Cutting Precision and Quality: Assessing the accuracy and finish of the cuts, including considerations of edge squareness and surface roughness.
- Operational Speed: Measuring the time taken to complete cuts for each material thickness, providing insight into productivity capabilities.
- Material Wastage: Quantifying the material wasted during cutting, which includes kerf width and material lost to thermal distortion.
- Consumables and Maintenance: Catalog the frequency of consumable replacements and maintenance requirements, which impact ongoing operational costs.
- Energy Consumption: Recording the energy requirements for each cutting method, contributing to the overall cost analysis.

Data Collection and Analysis

The research will employ a quantitative approach, gathering data through direct observation and measurement during the cutting processes. This data will be systematically recorded and compiled into a techno-economical table, facilitating a clear comparison between the cutting technologies across the selected parameters.

Techno-Economical and Economic Analysis

The compiled data will undergo a detailed techno-economical analysis, aiming to discern the cost-effectiveness and efficiency of each cutting technology relative to the others. This analysis will incorporate the direct costs associated with each cutting method, including equipment depreciation, consumables, energy consumption, and labor. Additionally, an economic calculation will be conducted to project the long-term financial implications of adopting each technology, considering factors such as operational efficiency, maintenance, and downtime.

Conclusion

The culmination of this methodology will provide a robust framework for evaluating the hypothesis, offering insights into the potential of 30kW lasers as a superior cutting technology. Through rigorous comparison and analysis, this research seeks to contribute valuable knowledge to the field, aiding in the informed decision-making of stakeholders within the metal fabrication industry.

4.2 Comparative Analysis of Cutting Technologies in Metal Fabrication

This chapter presents a concise techno-economical comparison of laser, plasma, and oxygen-cutting technologies, pivotal in metal fabrication. It aims to illuminate the operational efficiency, sustainability, and economic feasibility of these methods, guiding manufacturing enterprises towards optimal production decisions.

Initially, the chapter introduces the cutting machines for each technology, setting a foundation for understanding their capabilities and limitations. It then proceeds to compare the technologies on technical grounds, including quality, speed, and precision, to discern their respective advantages and constraints.

Sustainability and waste management are addressed next, evaluating the environmental impacts of each technology. This section emphasizes the significance of eco-friendly practices in metal cutting considering material wastage.

The chapter concludes with an economic comparison, analyzing costs associated with each cutting method, including initial investments, operational expenses, and maintenance. This final analysis offers insights into the cost-effectiveness of each technology.

4.2.1 Machine introduction

In this subchapter, the focus is on the comparative analysis of cutting-edge technologies utilized in metal sheet cutting: laser, oxy-fuel, and plasma. Central to the examination are three cutting machines that are present in TerasToorik company, each renowned for its technological advancements: the ESAB M3 360 Combirex DX3500, the ESAB M3 450 Combirex DX3500, and the Penta Laser BOTL VII Series. These machines exemplify the pinnacle of their respective cutting methods and provide invaluable insights into the evolution of metal fabrication.

To provide context for this analysis, it is essential to understand the current market dynamics in metal cutting technology. The industry is experiencing rapid evolution, driven by technological innovations and evolving market demands. Continual influx of new machines with enhanced features and performance metrics reshapes standards in metal fabrication. Against this backdrop, it becomes imperative to situate the analysis within the realm of ongoing market trends and emerging technologies.

As the exploration progresses through the comparison of these cutting technologies and machines, the objective is to furnish a comprehensive understanding of their respective strengths, limitations, and applicability in industrial settings. Furthermore, the aim is to incorporate insights from the latest advancements in metal cutting technology, thereby offering a holistic perspective on the state-of-the-art solutions available to manufacturers.

ESAB M3 360 Combirex DX3500 machine

Figure 4. ESAB M3 360 Combirex DX3500 machine

Source ESAB company website [19]

Firstly, the ESAB M3 360 Combirex DX3500 Figure 4. will be examined. A representative of oxyfuel cutting technology, reveals a machine of substantial and advanced functionality, tailored to meet the multifaceted demands of contemporary metal fabrication processes.[20][21]

One of its standout features is its cutting capacity. With the ability to handle sheets up to 2450 mm in width and 13000 mm in length, the ESAB M3 360 Combirex DX3500 empowers users to tackle projects of varying sizes. Furthermore, its substantial height of 2100mm and table height of 700mm ensure a comfortable working environment for operators, facilitating prolonged productivity without sacrificing ergonomic considerations. [20][21]

Versatility is another hallmark of the ESAB M3 360 Combirex DX3500. Its speed range, spanning from 50.8 to 25000 mm/min, allows users to adapt to diverse cutting requirements. Whether it is a high-speed production run or intricate detail work, this machine offers the precision and control needed to deliver optimal results.[20][21]

Moreover, the ESAB M3 360 Combirex DX3500 excels in its cutting capabilities. With a maximum thickness of 200mm, it demonstrates its prowess in handling a wide range of materials and thicknesses. This versatility makes it valuable across various industries, from heavy-duty fabrication to precision engineering.

It is important to recognize that achieving optimal accuracy with ESAB M3 360 Combirex DX3500 is dependent on several factors, including the thickness of the metal sheet being processed. While the machine provides the framework for precision cutting, meticulous calibration and adjustment are necessary to ensure consistent and accurate results across different material thicknesses.

ESAB M3 450 Combirex DX3500 machine

Figure 5. ESAB M3 450 Combirex DX3500 machine

Source ESAB company website [22]

Secondly, the ESAB M3 450 Combirex DX3500 Figure 5. will be examined. It represents a plasma cutting technology, distinguished by its comprehensive specifications and sophisticated functionalities, meticulously engineered to address the multifaceted demands of modern metal fabrication practices.

Central to its acclaim is the machine's exceptional cutting proficiency, characterized by its capacity to process metal sheets up to 2500 mm in width and 16000 mm in length. This capability enables the accommodation of a broad spectrum of project dimensions, facilitating enhanced efficiency and precision. The structural dimensions of the machine, with a height of 2100 mm and a table height of 750 mm, further contribute to a robust and ergonomically optimized workspace conducive to sustained operational productivity.[20][21]

Reflecting a parallel with its oxyfuel analog, the ESAB M3 450 Combirex DX3500 exhibits a remarkable range of cutting speeds, from 50.8 to 25000 mm/min. This extensive range allows for flexible adaptation to varied cutting requirements, ensuring superior performance across diverse applications.[20][21]

In terms of cutting proficiency, the machine's maximum thickness capacity stands at 60 mm, allowing for the processing of an extensive variety of materials and thicknesses with exceptional precision and uniformity. The precision of the ESAB M3 450 Combirex DX3500, which varies from 1 to 3 mm based on the metal sheet's thickness, epitomizes its reliability in achieving accurate cutting outcomes.

An additional noteworthy feature of the ESAB M3 450 Combirex DX3500 is its beveling capability, which reaches up to a maximum of 45 degrees, both positive and negative. This functionality not only amplifies the machine's versatility but also streamlines the fabrication of intricate geometries, thereby enhancing the efficacy of metal-cutting operations. The capacity to execute bevels on holes further broadens its application scope, offering increased adaptability in various fabrication endeavors.

Penta Laser BOTL VII Series machine

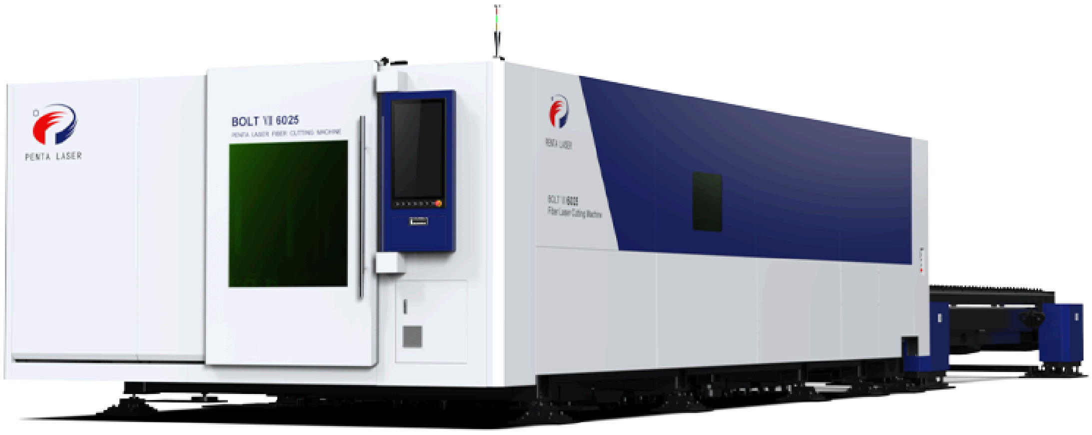


Figure 6. Penta Laser BOTL VII Series machine

Source Penta Laser company website [23]

Thirdly, the Penta Laser BOTL VII Series Figure 6. will be examined. This laser-cutting machine represents the pinnacle of precision and power in modern manufacturing technologies, particularly suited for the sheet metal industry. The Penta Laser BOTL VII Series is designed to handle large-scale materials, accommodating metal sheets up to 3000mm in width and 13000mm in length, which underscores its capability in handling expansive manufacturing tasks.[23]

One of the standout features of this machine is its rapid cutting speed, which varies between 200 to 240 meters per minute. This speed not only enhances productivity but also reduces turnaround time significantly, making it an ideal choice for environments where efficiency is paramount. Additionally, the 40kW power output of the machine is exceptional, particularly for laser-cutting machines, providing it with the ability to cut through thicker materials with ease while maintaining high levels of energy efficiency.[23]

The Penta Laser BOTL VII Series is equipped with dual tables that significantly enhance its operational efficiency. The primary table, often referred to as the 'working table,' is situated within the machine and is designated for the cutting processes, while the secondary table serves as a sorting space for already cut parts, facilitating a smooth transition between cutting and post-processing stages. This setup helps maintain workflow continuity and minimize downtime. Additionally, the machine features a hydraulic pallet exchanger that boosts productivity and safety by allowing rapid and secure switching between the two tables, accommodating different materials or job setups with reduced idle times.[23]

The precision of the Penta Laser BOTL VII Series is guaranteed by its advanced Precitec cutting head. This cutting head is renowned for its accuracy and consistency, ensuring that each cut is executed with the highest level of precision. This not only improves the quality of the finished products but also reduces material waste due to cutting errors.[24]

Cutting machines specifications summary

Table 4.1 provides a summary of the specifications for cutting machines, each representing a distinct cutting technology: oxyfuel, plasma, and laser. The table is organised into several key rows including 'Cutting Technology Type', 'Maximum Material Dimensions', 'Maximum Material Thickness', 'Material Compatibility', 'Precision', 'Cutting Speed', and 'Other Features'.

Table 4.1 Cutting machines specifications summary

Specifications	ESAB M3 360 Combirex DX3500 machine	ESAB M3 450 Combirex DX3500 machine	Penta Laser BOTL VII Series machine
Cutting technology type	Oxyfuel	Plasma	Laser
Maximum material dimensions, mm	2450x13000	2500x16000	3000x13000
Maximum material thickness, mm	200	60	55
Material compatibility	Carbon steel, stainless steel	Conductive metals	Carbon steel, stainless steel, various non-metals
Precision, mm	1-2	1-2	0.1-1
Maximum cutting speed, mm/min	25000	25000	50000
Other features	-	Beveling	Exchangeable tables

Current market situation

In the rapidly evolving landscape of sheet metal cutting technologies, laser cutting continues to outpace other methods in terms of technological advancements and market offerings. A notable development this year is the introduction of the 60kW Penta Laser BOLT VII Series. This new laser machine marks a significant leap forward, offering greater capabilities in cutting thicker materials and achieving higher speeds. The increased power allows for a broader variety of sheet thicknesses to be cut, enhancing versatility and productivity for high-demand manufacturing environments. [25]

Conversely, the market for plasma and oxy-fuel cutting technologies has shown more modest advancements. Recent updates in these areas have primarily focused on incremental improvements in efficiency and electricity consumption. While these changes contribute to better operational cost-effectiveness, they do not represent substantial shifts in capability or technology.

An interesting innovation within the plasma cutting sector is the development of plasma cutting tables that operate underwater. This approach addresses several environmental and safety concerns traditionally associated with plasma cutting. By submerging the cutting area, these tables reduce noise pollution, eliminate the need for a dust collector, and significantly decrease the risk of dangerous arc flashes. This not only enhances the safety profile of plasma cutting but also contributes to a cleaner and quieter operational environment.[26]

These contrasting trends highlight the dynamic nature of the sheet metal cutting machine market, with laser technology leading significant breakthroughs that expand the boundaries of what can be achieved, while plasma and oxy-fuel technologies continue to focus on optimizing existing processes and enhancing safety and environmental compliance.

4.2.2 Technological comparison

In the intricate domain of metal fabrication, the efficacy of cutting technologies is pivotal to achieving optimal production outcomes. This chapter provides a rigorous technological comparison of three principal cutting methods—laser, plasma, and oxy-fuel—each distinguished by unique operational mechanics and suitable for different industrial applications. The comparative analysis is structured to methodically dissect the multifaceted aspects of these technologies, providing a holistic understanding of their performance in contemporary manufacturing environments.

The examination begins by assessing the cutting time and accuracy of laser, plasma, and oxy-fuel technologies. Utilizing empirical data gathered from production settings, this section aims to quantify the operational efficiency and precision of each method, factors that are critical for meeting the stringent quality demands of modern manufacturing. Following this, the analysis delves into the environmental impact of each technology by comparing the waste generated during the cutting process. This comparison not only reflects the sustainability of each method but also influences the selection of technology based on waste minimization practices.

Subsequently, the discussion shifts focus to the heat distribution characteristics inherent to each cutting technique. Heat management is crucial as it directly affects material properties and the integrity of the final product. By exploring how each technology manages thermal input, insights into their suitability for different materials and the potential for thermal deformation are gained.

The chapter continues with an evaluation of material compatibility, a key factor that dictates the versatility of each cutting method. This section assesses the range of materials each technology can effectively process, highlighting their adaptability across various industrial sectors. The final aspect of the comparison involves analyzing the thickness ranges that each technology can handle, an essential consideration that impacts their applicability for cutting tasks involving different material dimensions.

Through this structured comparison, the chapter seeks to equip readers with a nuanced understanding of laser, plasma, and oxy-fuel cutting technologies. By comprehensively evaluating their time efficiency, accuracy, waste generation, heat distribution, material compatibility, and thickness handling capabilities, this analysis not only contributes to the academic discourse on manufacturing technologies but also aids practitioners in making informed decisions about the optimal cutting technology for specific applications.

Accuracy and time

To comprehensively assess the technological efficiency of laser, plasma, and oxy-fuel cutting methods, an empirical analysis was conducted focusing on the time required to cut metal sheets of varying thicknesses and nesting configurations. This analysis is crucial in highlighting the operational differences between the three technologies under diverse manufacturing scenarios. Data from production environments were methodically collected and presented in a series of tables, each illustrating specific conditions and results.

Table 4.2 and Figure 7. present a comparative analysis of the cutting times for 5 mm thick metal sheets. The findings clearly indicate that laser cutting is significantly faster compared to the other two technologies, with plasma cutting being the second fastest and oxy-fuel the slowest. Specifically, laser cutting is shown to be twice as fast as plasma cutting (0.5 times the duration of plasma cutting) and oxy-fuel is considerably slower, taking 1.5 times longer than plasma to complete the same cuts. This discrepancy highlights the efficiency of laser technology in handling relatively thin sheets, where speed is substantially enhanced due to the focused energy and minimal kerf width produced by the laser beam.

Table 4.2 Time needed for different technologies to cut 5 mm metal sheet

Graphical representation	Sheet dimensions, mm	Cutting length, m	Cutting time for plasma, min	Cutting time for oxy-fuel, min	Cutting time for laser, min
Appendix 1	1107x2582	113.5	61	92	31
Appendix 2	1486x2780	84	45	68	23
Appendix 3	1500x1402	55.8	30	45	15
Appendix 4	1500x2970	50.2	27	41	14
Appendix 5	1500x6000	52.1	28	42	14
Appendix 6	1500x6000	57.7	31	47	16
Appendix 7	1500x6000	135.8	73	110	37
Appendix 8	1500x6000	238.1	128	192	64
Appendix 9	1510x2852	133.9	72	108	36
Appendix 10	1510x3459	223.2	120	180	60

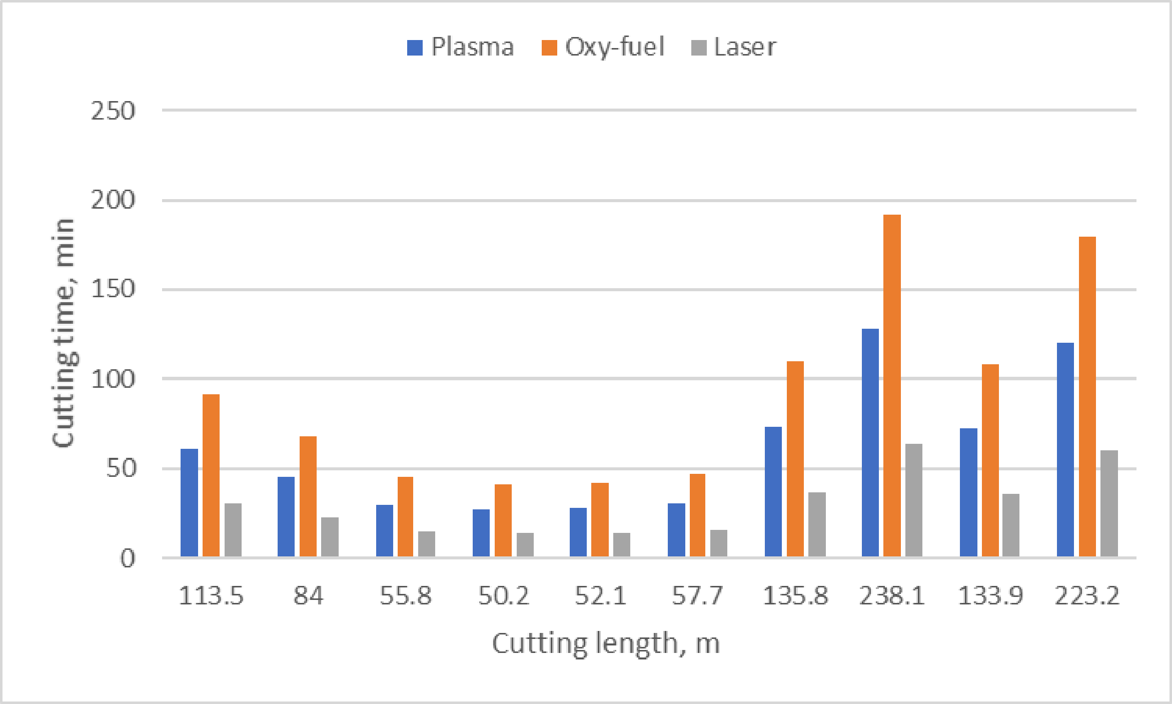


Figure 7. Comparison of cutting times for three technologies for 5mm thick metal sheets

Table 4.3 and Figure 8., which focus on 25 mm thick metal sheets, extend this comparison to a different setup, maintaining the same order in terms of speed but showing a slight adjustment in comparative times. In this scenario, laser cutting maintains its superior speed, operating at twice the speed of plasma (0.5 times the duration of plasma cutting), while oxy-fuel shows a modest improvement but remains slower, taking 1.25 times the duration of plasma.

Table 4.3 Time needed for different technologies to cut 25 mm metal sheet

Graphical representation	Sheet dimensions, mm	Cutting length, m	Cutting time for plasma, min	Cutting time for oxy-fuel, min	Cutting time for laser, min
Appendix 11	615x1368	50.2	27	34	14
Appendix 12	651x1557	74.4	40	50	20
Appendix 13	857x2050	50.2	27	34	14
Appendix 14	1010x1500	37.2	20	25	10
Appendix 15	2000x6000	46.5	25	31	13
Appendix 16	2000x6000	93	50	63	25
Appendix 17	2050x563	70.7	38	48	19

Appendix 18	2050x2320	76.3	41	51	21
Appendix 19	2050x5803	124.6	67	84	34
Appendix 20	2050x6476	360.8	194	243	97

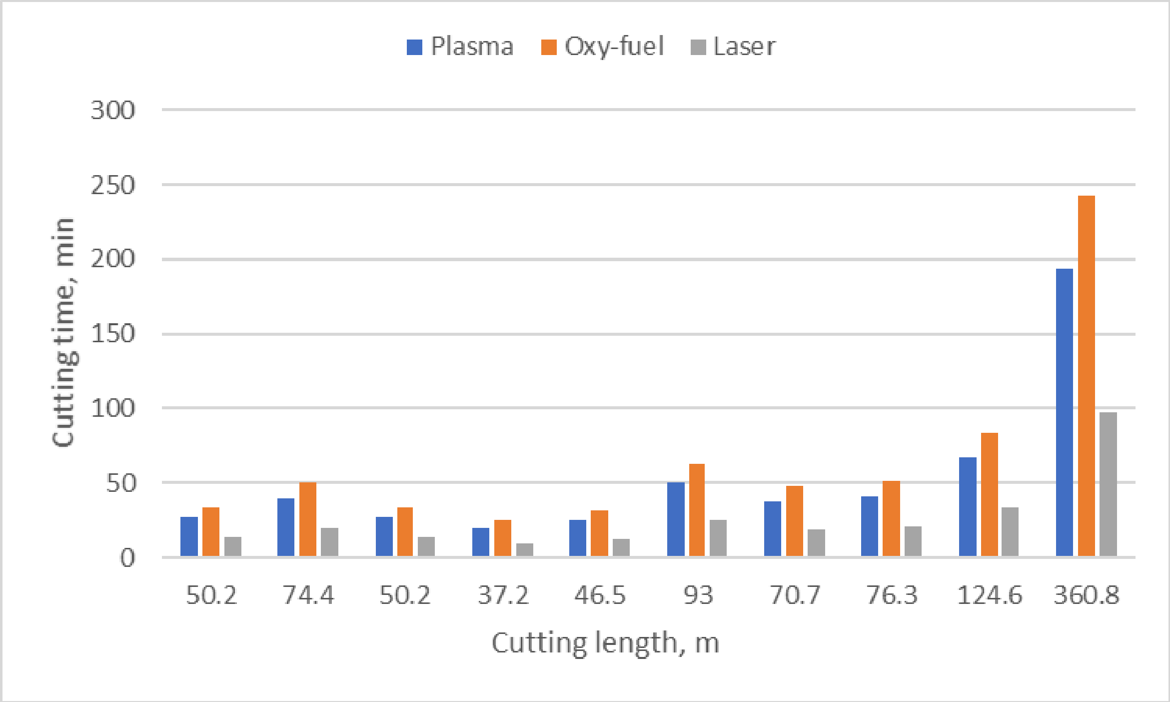


Figure 8. Comparison of cutting times for three technologies for 25mm thick metal sheets

Table 4.4 and Figure 9., explores yet another variation, with 40mm thick sheets, further supporting the consistency of laser cutting's superior speed. In this case, laser cutting is four times faster than plasma (0.25 times the duration of plasma cutting), whereas oxy-fuel maintains a consistent slower pace, taking 1.25 times longer than plasma.

Table 4.4 Time needed for different technologies to cut 40 mm metal sheet

Graphical representation	Sheet dimensions, mm	Cutting length, m	Cutting time for plasma, min	Cutting time for oxy-fuel, min	Cutting time for laser, min
Appendix 21	400x558	79.7	39	48.8	29
Appendix 22	700x6000	200.4	98	123	74
Appendix 23	1000x776	175.8	86	108	65
Appendix 24	1808x1473	159.5	78	98	59
Appendix 25	2000x8142	201	98	123	74

Appendix 26	2000x8900	412.9	202	253	152
Appendix 27	2013x2000	57.2	28	35	21
Appendix 28	2020x3256	318.9	156	195	117
Appendix 29	2050x4760	92	45	56	34
Appendix 30	2050x10900	451.8	221	276	166

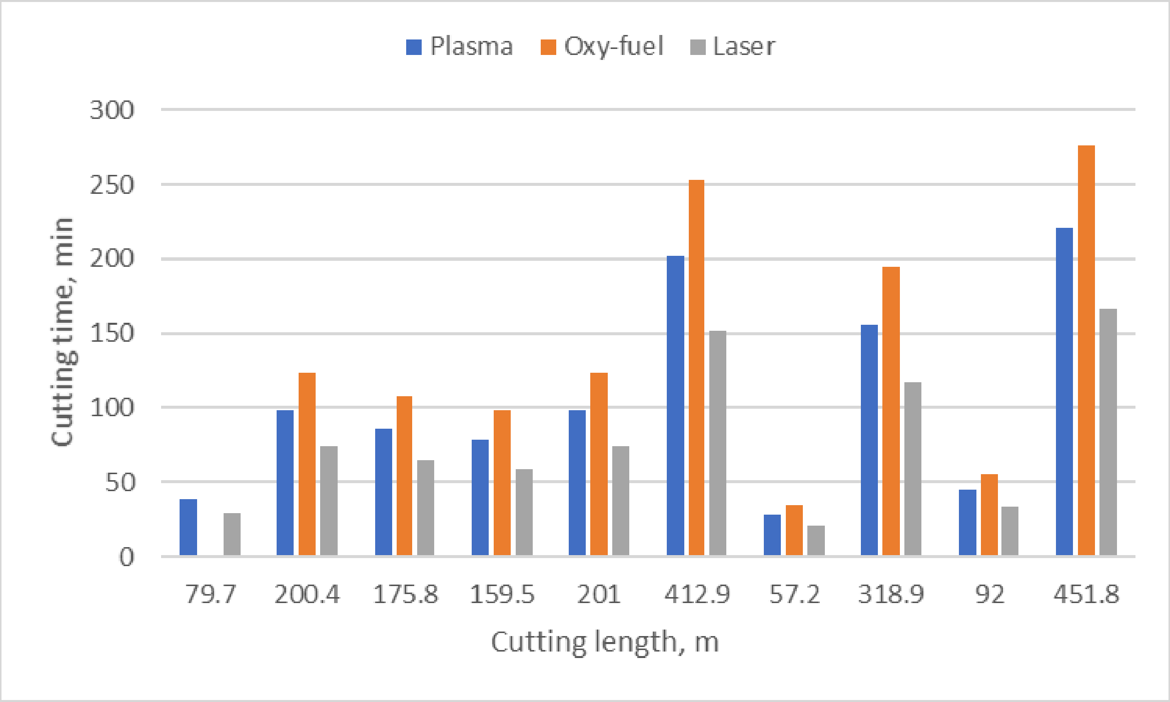


Figure 9. Comparison of cutting times for three technologies for 25mm thick metal sheets

Effective nesting plays a pivotal role in optimizing the operational efficiency of sheet metal cutting technologies. Beyond material savings, strategic nesting significantly influences the overall speed and time efficiency of the cutting process, primarily by streamlining the sequence of cuts and reducing the time spent in non-cutting movements, known as “rapid time”.

Rapid time is the duration during which the cutting head moves between cut paths without actively cutting material. Minimizing this time is crucial as it directly affects the throughput of the cutting operation. An optimized nesting plan ensures that the sequence of parts to be cut is arranged in such a way that the travel path of the cutting head is shortened. This involves strategic placement of parts so that the cutting head moves in a continuous, efficient path with minimal retraction or unnecessary travel.

Moreover, effective nesting also involves consideration of the kerf, or the width of the cut removed by the cutting tool, which is particularly relevant in processes like plasma and laser cutting where the beam width can influence how closely parts can be nested. By adjusting the layout to account for the kerf, the software can place parts closer together without the risk of them merging during cutting, further enhancing material utilization and so the accuracy.

Among the three primary cutting methods—laser, plasma, and oxy-fuel—there are distinct differences in achievable accuracy, largely influenced by the mechanics of each technology and the interaction between the cutting tool and the material.

Laser cutting stands out for its accuracy and precision, primarily due to the very narrow laser beam used in the cutting process. This technology allows for extremely fine cuts, making it ideal for intricate designs and detailed work. The precision of laser cutting can achieve tolerances as tight as a few thousandths of an mm, which is significantly higher than what can typically be achieved with other cutting methods.

In contrast, plasma cutting, while capable of producing very good results, generally offers less precision than laser cutting. The wider kerf associated with plasma cutting can lead to edge quality issues, such as dross and a rougher cut surface. Oxy-fuel cutting, on the other hand, is the least precise of the three technologies. It is primarily used for cutting thicker steel plates and is characterized by a considerably wider kerf, which can lead to material deformations. The accuracy of oxy-fuel cutting is generally sufficient for applications where tolerances are not tightly controlled, but it may require additional machining or finishing processes to achieve the desired final dimensions.

In metal fabrication, the setting time for cutting machines employing oxyfuel, laser, and plasma technologies has become increasingly negligible due to advancements in technology. Modern iterations of these machines are designed with enhanced automation and user-friendly interfaces, which significantly streamline the setup processes. Consequently, the initial preparation times—encompassing machine calibration, system checks, and material positioning—are quite similar across these technologies. This uniformity in setting times facilitates a more efficient transition between different cutting tasks and reduces downtime, thereby optimising operational throughput in industrial settings.

Through this analysis, it is evident that laser cutting generally offers the best performance in terms of speed across different material thicknesses, followed by plasma and oxy-fuel. This superiority in cutting speed, coupled with its ability to maintain high precision, makes laser cutting a preferred technology in scenarios where both quality and efficiency are critical.

Waste

In the context of sustainable manufacturing practices, the generation of waste is a critical factor when assessing the efficiency and environmental impact of sheet metal cutting technologies. Laser, plasma, and oxy-fuel cutting, while all effective in their respective domains, exhibit significant differences in waste production, primarily due to the mechanics of each method and the strategies employed for part layout and cutting.

Laser cutting technology is distinguished by its ability to minimize waste through highly efficient nesting capabilities. The narrower kerf width and shorter lead-in requirements enable parts to be positioned closer together, both part-to-part and part-to-sheet. This close nesting is feasible because the precision of the laser allows for a minimal amount of material to be removed during the cutting process, thereby maximizing material utilization and significantly reducing scrap.

Plasma cutting, in contrast, generates more waste compared to laser cutting due to its inherently wider kerf. The physics of plasma cutting necessitates a larger space for the pressurized gas to expel from the nozzle, initiating the cutting reaction. This wider kerf means that more material is removed during the cutting process, leading to increased material waste and less efficient use of the metal sheet. The requirement for wider part spacing thus diminishes the potential for tight nesting, consequently elevating the volume of scrap produced.

Oxy-fuel cutting presents a different aspect of waste generation. Unique among the three technologies, oxy-fuel cutting allows the cutting process to be initiated outside the boundaries of the material, which can reduce lead-in waste when the cut starts at the sheet edge. However, like plasma, oxy-fuel cutting also involves a wider kerf, which increases the amount of material consumed during cutting. Although it can sometimes offer advantages in reducing waste through strategic starting points, the overall efficiency of material usage is generally lower than that of laser cutting.

These differences underscore the importance of selecting the appropriate cutting technology based on material efficiency and waste minimization. While each technology has its merits, laser cutting stands out in terms of reducing waste and enhancing material utilization, making it a preferable choice for applications where precision and sustainability are paramount.

Heat distribution

The distribution of heat during the cutting process significantly influences the integrity and dimensional accuracy of the finished parts. In comparing laser, oxy-fuel, and plasma cutting technologies, each method exhibits distinct characteristics in terms of heat management and the resultant thermal deformation.

Laser cutting is recognized for its high-speed operation and minimal heat input into the material being cut. Due to the localized and rapid nature of the laser beam, the surrounding areas of the part experience minimal thermal effects. This aspect makes laser cutting particularly advantageous for producing long parts where the risk of thermal deformation needs to be minimized. The precision and speed of the laser effectively limit the extent of the heat-affected zone (HAZ), reducing the likelihood of warping or dimensional changes in the workpiece.

Conversely, oxy-fuel cutting, while slower, inherently involves a high degree of thermal input due to the combustion process used to cut through materials, typically thick steel plates. This method heats a larger area of the material, which can lead to significant thermal deformation. However, due to the slow cutting speed, the heat has more time to distribute evenly, which can somewhat mitigate severe localized warping. Still, parts often need to be cut with considerable allowances to compensate for potential dimensional inaccuracies, requiring subsequent machining or finishing to achieve precise dimensions.

Plasma cutting presents a middle ground in terms of speed but requires specific techniques to manage the thermal output effectively. Due to the intense and concentrated heat generation of the plasma arc, there is a substantial risk of thermal deformation, particularly in thinner or more intricate parts. To counteract this, additional methods such as the use of tabs are commonly employed. These tabs act as small bridges that connect the part to the main sheet, stabilizing the material during cutting and cooling phases to prevent the part from warping or detaching prematurely.

This method helps maintain the structural integrity and dimensional accuracy of the parts but adds complexity to the cutting process.

Material Compatibility

Material compatibility is a decisive factor in the selection of cutting technologies within the manufacturing industry. Laser, plasma, and oxy-fuel cutting exhibit distinct preferences and capabilities when it comes to the types of materials they can effectively process, each suited to specific applications based on the material's physical and chemical properties.

Laser cutting is highly versatile but exhibits some limitations with certain materials. For instance, laser technology is less effective with rusted materials, necessitating careful selection of carbon steel such as S355MC. Other types of carbon steels may require additional surface preparation like cleaning (removal of oxidize layer on the material) to ensure optimal cutting quality. This is due to the laser's sensitivity to inconsistencies in material composition and surface texture, which can affect the cutting efficiency and quality of the edges. However, laser cutting excels with stainless steel and other non-ferrous materials, offering a significant advantage in that it leaves clean, precise cuts without burned edges—a common issue in more traditional cutting technologies. Additionally, laser cutters are capable of processing various non-metals, although this capability is only briefly relevant for the scope of this thesis.

Plasma cutting, in contrast, is particularly effective for conductive metals. The nature of the plasma arc, which is generated between the cutter and the electrically conductive material, makes it ideal for cutting through various metals with electrical conductivity efficiently and quickly. This method, however, is not suitable for non-conductive materials, which limits its applicability compared to laser cutting.

Oxy-fuel cutting is predominantly effective with carbon steels of all types. This method relies on the combustion of oxygen with the base material at high temperatures, a process that is naturally suited to carbon-rich steels. Oxy-fuel's capability to handle thicker and rust-prone steels without the need for extensive surface preparation presents a robust option for heavy industrial applications. However, its use is generally restricted to ferrous materials and is not suitable for non-metals or materials that are non-reactive to the oxy-fuel process.

Each cutting technology thus presents unique advantages and constraints regarding material compatibility. The choice of method depends significantly on the specific requirements of the project, including material type, desired cut quality, and production efficiency.

Thickness Range

The capacity to cut through varying thicknesses of materials is a critical aspect of sheet metal cutting technologies, influencing their applicability across different industrial needs. Oxy-fuel, plasma, and laser cutting technologies each exhibit unique capabilities in handling material thickness, which profoundly affects their operational use and effectiveness in specific applications.

Oxy-fuel cutting is notable for its ability to handle the widest range of material thicknesses, making it invaluable in industries where cutting very thick materials is common. The high-temperature flame of oxy-fuel cutting can easily manage large thicknesses, offering substantial versatility in heavy manufacturing environments.

Plasma cutting offers effective performance for materials up to 40mm thick but has limitations with intricate shapes, particularly when dealing with narrow spaces and cavities. The nature of the plasma arc, which is broader and less precise than a laser, restricts its ability to perform detailed cuts within thicker materials, limiting its utility in applications requiring high precision or complex patterns.

Laser cutting technology, while initially suited to thinner materials, has advanced significantly, now accommodating metal sheets up to 50 mm thick. The continuous advancements in laser technology expand its applicability, combining inherent precision with the ability to handle increasingly thicker materials.

In terms of cutting precision for smaller features such as holes, oxy-fuel and plasma cutting techniques specify that the minimum diameter of the holes should be no less than 0.8 times the thickness of the metal sheet. For example, in a 10 mm thick plate, the smallest hole diameter achievable would be 8 mm. This requirement ensures structural integrity and avoids excessive thermal impact on smaller features. In contrast, laser cutting technology allows for much finer detail, capable of producing holes with diameters as small as 0.25 to 0.5 times the thickness of the metal sheet. This level of precision enables laser cutting to produce more intricate and closely spaced features within a part, which is especially valuable in high-specification engineering applications.

Technological comparison summary

Table 4.5, titled "Technological Comparison Summary," provides a systematic overview of the key operational characteristics of three primary metal sheet cutting technologies: oxyfuel, laser, and plasma. The table delineates these technologies across six different metrics: accuracy, cutting time, waste production, heat distribution, material compatibility, and thickness range. For accuracy, the laser technology offers superior precision with a range between 0.1 and 1 mm, whereas both oxyfuel and plasma maintain a broader range of 1-2 mm. Regarding cutting time, laser cutting is notably faster, achieving speeds 0.5 times faster than plasma, while oxyfuel is the slowest, with speeds 1.25 times slower than plasma. Waste generation is minimized with laser technology due to its narrow kerf, which allows for closer spacing and less material wastage, followed by plasma and then oxyfuel, which generates the most waste. Heat distribution varies significantly, with laser technology producing minimal heat due to its rapid operation, plasma providing a moderate balance, and oxyfuel generating considerable heat, necessitating extensive countermeasures. In terms of material compatibility, lasers can process both metals and nonmetals, although they are sensitive to material conditions such as rust, plasma cutters are restricted to conductive metals, and oxyfuel is most effective with all types of carbon steels. Finally, the thickness range that each technology can handle also differs markedly, with oxyfuel capable of cutting up to 200 mm, significantly more than the 50 mm and 40 mm limits of laser and plasma respectively.

Table 4.5 Technological comparison summary

Feature	Oxyfuel	Plasma	Laser
Accuracy	1-2 mm	1-2 mm	0.1-1 mm
Cutting time	1.25 times slower than Plasma	Baseline speed	0.5 times faster than Plasma
Waste	Highest waste	Moderate waste	Least waste
Heat distribution	Slow cutting causes more heating; needs countermeasures	Moderate speed and heating	Faster cutting, minimal heating
Material compatibility	Effective with all types of carbon steel	Requires conductive metals only	Cuts metals and non-metals; sensitive to rust
Thickness range	Up to 200 mm	Up to 40mm with shape limitations	Up to 50 mm

4.2.3 Economical comparison

The research examines operational metrics including gas and electricity consumption, equipment depreciation, labor costs, and maintenance for three primary metal cutting technologies—plasma, oxy-fuel, and laser—using data collected from Terastoorik AS. Gas consumption rates and related costs were sourced directly from the factory. The electricity costs were calculated based on the average exchange price for March 2024, obtained from Enefit web page [27]. The study considers the cost of nozzles, cathodes (specific to plasma), and lenses (specific to laser), by amortizing their costs over their respective lifespans to determine hourly costs. Labor costs, inclusive of taxes and mandatory payments, were sourced from palga.ee, reflecting the total cost of employing an operator.

Cost analysis

Machine hours were determined by assuming an 8-hour workday with two shifts, where each shift includes a minimum of four hours of cutting time. The next parameter is the cost of remuneration of the employee. The author takes into account all costs, that is all taxes and payments required by law, since this shows the real cost of paying one employee. Since salary information is sensitive, the author took from the source palga.ee [28] employer expenses per employee (specialty - operator). Equipment costs were derived from average vendor prices and were amortized over a 10-year lifespan to calculate the annual and subsequently hourly machine costs. Similar methodology was applied to maintenance costs.

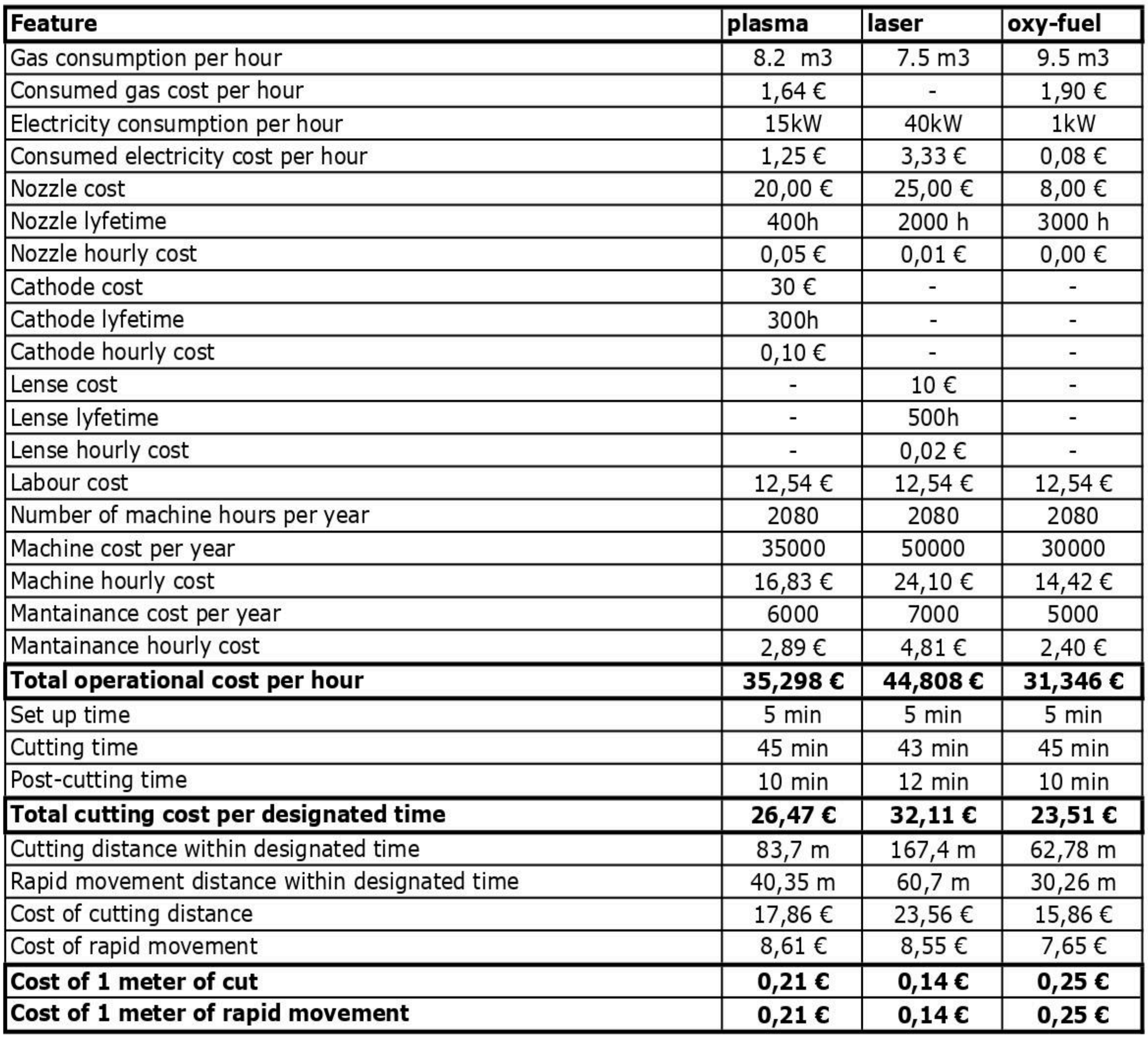
Operational costs were compiled from various components for each technology. The cost per hour included gas, electricity, consumables (nozzles, cathodes for plasma, and lenses for laser), labor, and the aggregated cost of machine operation and maintenance. Plasma and oxy-fuel technologies showed similar operational times, but the laser technology incurred higher post-cutting times due to the complexities involved in removing the cut parts from narrow spaces.

Operational efficiency and cutting costs

The study further breaks down the total operational costs into individual cutting times, incorporating both the actual cutting process and the rapid movements between cuts. Notably, the rapid movement associated with the laser technology is less costly due to smaller distances between parts, impacting the overall efficiency and cost.

The critical metric of cost per meter of cut was calculated by dividing the total cutting costs by the distance cut within the designated time. This figure serves as a pivotal comparison point, highlighting the cost-effectiveness of each technology in a production environment.

Table 4.6 Economical comparison of three cutting tehcnologies (25mm thick metal sheet)



Feature	plasma	laser	oxy-fuel
Gas consumption per hour	8.2 m3	7.5 m3	9.5 m3
Consumed gas cost per hour	1,64 €	-	1,90 €
Electricity consumption per hour	15kW	40kW	1kW
Consumed electricity cost per hour	1,25 €	3,33 €	0,08 €
Nozzle cost	20,00 €	25,00 €	8,00 €
Nozzle lyfetime	400h	2000 h	3000 h
Nozzle hourly cost	0,05 €	0,01 €	0,00 €
Cathode cost	30 €	-	-
Cathode lyfetime	300h	-	-
Cathode hourly cost	0,10 €	-	-
Lense cost	-	10 €	-
Lense lyfetime	-	500h	-
Lense hourly cost	-	0,02 €	-
Labour cost	12,54 €	12,54 €	12,54 €
Number of machine hours per year	2080	2080	2080
Machine cost per year	35000	50000	30000
Machine hourly cost	16,83 €	24,10 €	14,42 €
Mantainance cost per year	6000	7000	5000
Mantainance hourly cost	2,89 €	4,81 €	2,40 €
Total operational cost per hour	**35,298 €**	**44,808 €**	**31,346 €**
Set up time	5 min	5 min	5 min
Cutting time	45 min	43 min	45 min
Post-cutting time	10 min	12 min	10 min
Total cutting cost per designated time	**26,47 €**	**32,11 €**	**23,51 €**
Cutting distance within designated time	83,7 m	167,4 m	62,78 m
Rapid movement distance within designated time	40,35 m	60,7 m	30,26 m
Cost of cutting distance	17,86 €	23,56 €	15,86 €
Cost of rapid movement	8,61 €	8,55 €	7,65 €
Cost of 1 meter of cut	**0,21 €**	**0,14 €**	**0,25 €**
Cost of 1 meter of rapid movement	**0,21 €**	**0,14 €**	**0,25 €**

Comparative analysis for total operational cost

The structure for table 4.6 was inspired by "TECHNO-ECONOMICAL COMPARISON OF CUTTING MATERIAL BY LASER, PLASMA AND OXYGEN" research[16] and approach for calculating the total operational cost was inspired by other research "The Dynamical Behaviour of Gas Jets in Laser C utting"[29].

For the economical comparison of the three cutting technologies—plasma, oxy-fuel, and laser—a 25 mm thick metal sheet was selected as the middle observed thickness to ensure uniformity in the testing conditions across all technologies. The material used was S355J2 [30], a commonly employed structural steel known for its weldability and high strength. This choice of material and thickness represents a typical scenario in industrial applications, providing a relevant basis for assessing the cost-effectiveness and operational efficiency of each cutting method under comparable conditions.

In the analysis of operational costs for metal sheet cutting technologies at Terastoorik AS, the study examines the comprehensive hourly expenses associated with plasma, laser, and oxy-fuel cutting. These operational costs incorporate all phases of the cutting process: setup, actual cutting, and post-cutting activities. The total operational costs per hour were found to be €35.298 for plasma, €44.808 for laser, and €31.346 for oxy-fuel. These figures are visualized in respective pie charts (Figures 10, 11, and 12), which detail the distribution of costs for each technology, including consumables like gas and electricity, nozzle and cathode (for plasma) or lens (for laser) depreciation, labor, machine operation, and maintenance.

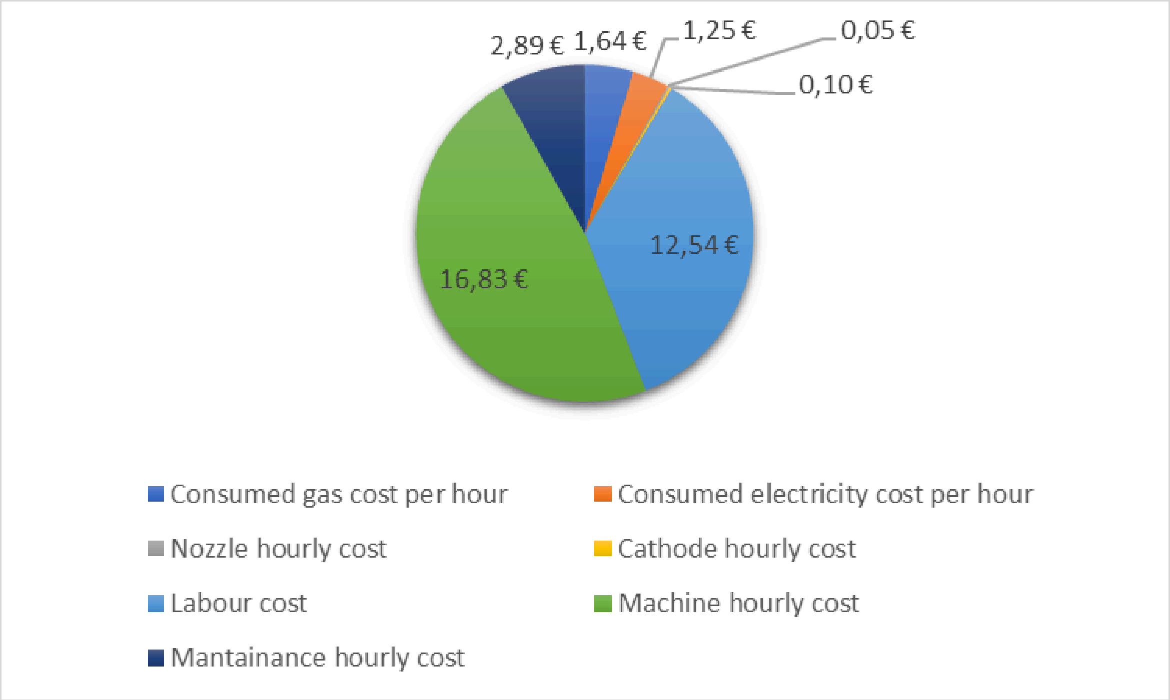


Figure 10. Total operational cost per hour for plasma machine

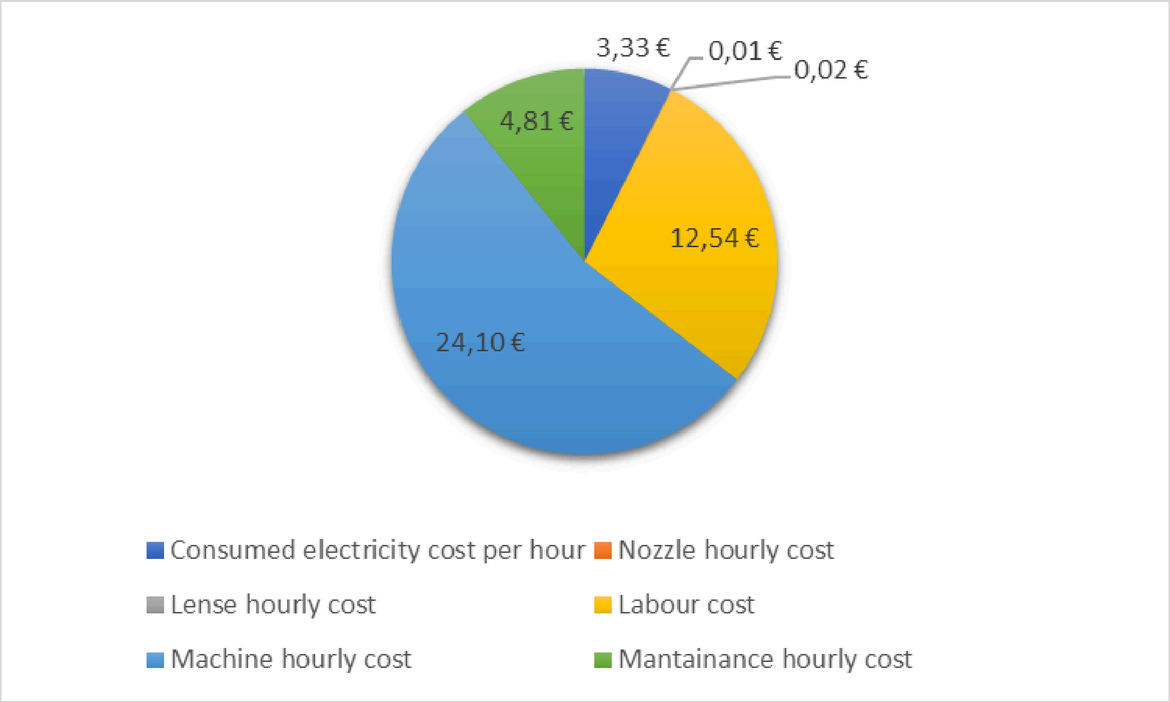


Figure 11. Total operational cost per hour for laser machine

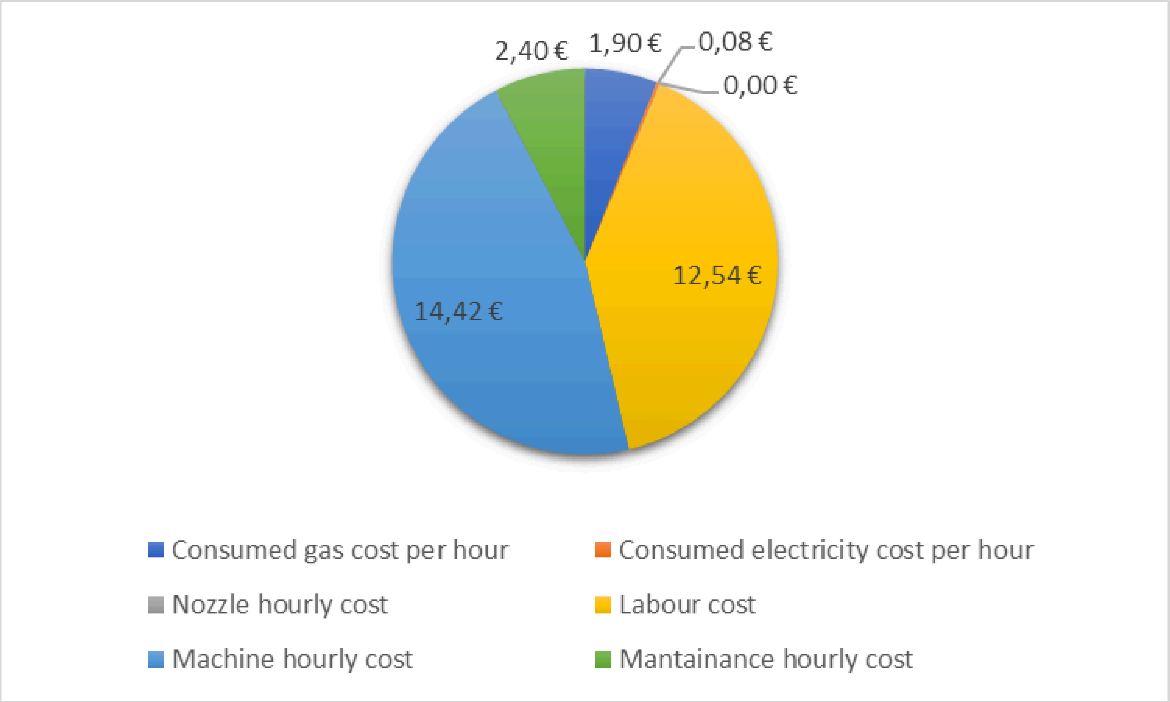


Figure 12. Total operational cost per hour for oxy-fuel machine

While these operational costs are critical for understanding the immediate hourly expenditure of each technology, they do not encompass the entire economic picture. Particularly, the plasma technology, despite its lower operational cost compared to laser, requires further analysis through the total cutting costs due to its operational characteristics and the nature of the parts it produces.

Next an analysis was conducted on the total cutting costs within one hour of operation for each machine. The costs were recorded as follows: plasma at €26.48, laser at €32.11, and oxy-fuel at €23.51. These values represent the direct costs associated with the actual cutting operations, encompassing setup time, the cutting process itself, and post-cutting time.

Comparison of total cutting costs

Upon comparison, the oxy-fuel technology emerges as the most cost-effective option per hour of operation, with the total cutting cost amounting to €23.51. This cost efficiency could be attributed to the lower fuel and operational demands of the oxy-fuel technology compared to its counterparts. On the other hand, the laser technology incurs the highest cost at €32.11 per hour. This increased cost likely results from the higher energy requirements and the cost of consumables like lenses, which are specific to laser machines. Plasma, while more expensive than oxy-fuel, still remains less costly than laser, with an operational cost of €26.48 per hour.

Significance of cost per meter of cut

The next step in the analysis involves calculating the cost per meter of cut, which is considered the most important parameter for assessing economic efficiency in the metal sheet cutting industry. This metric directly affects the profitability and operational efficiency, as it reflects the cost effectiveness of the cutting process per unit length of material cut.

The data obtained from Terastoorik AS regarding the cutting efficiency and costs of different metal cutting technologies—plasma, laser, and oxy-fuel—provides an insightful comparison of operational performance.

Performance and efficiency analysis

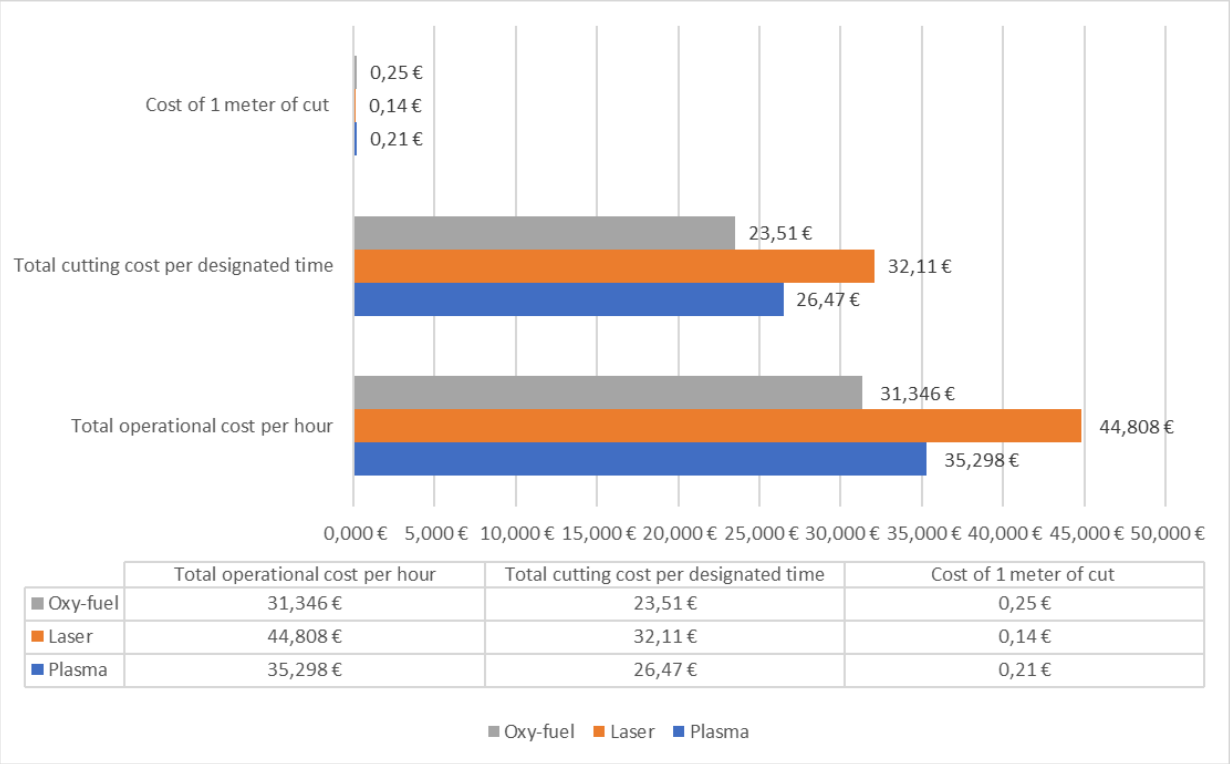
- Plasma Cutting: Over a span of 45 minutes, plasma technology was able to cut a distance of 83.7 meters with an additional rapid movement distance of 40.35 meters. The cost per meter for plasma cutting was calculated to be €0.21.
- Laser Cutting: Laser technology, on the other hand, demonstrated superior cutting distance efficiency. In 43 minutes, it achieved a cutting distance of 167.4 meters and a rapid movement distance of 60.7 meters. This resulted in a notably lower cost of €0.14 per meter, indicating higher efficiency and productivity.
- Oxy-Fuel Cutting: Oxy-fuel technology cut 62.78 meters with a rapid movement distance of 30.26 meters during the same approximate time frame. The cost per meter of cut for oxy-fuel was the highest at €0.25.

Comparative analysis

In evaluating the economic efficiency of metal sheet cutting technologies, a detailed analysis was conducted on the operational and cutting costs for plasma, laser, and oxy-fuel technologies Figure 13. at Terastoorik AS. Despite higher total operational costs and total cutting costs for the laser technology (€44,408 per hour and €32.11 respectively), it emerges as the most cost-effective in terms of the cost per meter of cut. Specifically, the laser technology achieves a cost of €0.14 per meter, compared to €0.21 for plasma and €0.25 for oxy-fuel.

Laser technology not only offers lower costs per meter but also excels in productivity and quality. It cuts twice as many parts as the other technologies within similar time frames, providing higher accuracy and better surface finish. These qualities enhance the value of the end products, potentially justifying the higher upfront costs associated with laser operation.

In contrast, plasma and oxy-fuel technologies, while having lower hourly operational costs (€35,298 for plasma and €31,346 for oxy-fuel), do not achieve the same level of cost-efficiency per meter of cut or the quality outputs as the laser. The plasma's cost efficiency is moderate, and oxy-fuel, despite being the cheapest in operational costs, ends up being the most expensive per meter of cut due to its slower cutting speeds and lower precision.



	Total operational cost per hour	Total cutting cost per designated time	Cost of 1 meter of cut
■ Oxy-fuel	31,346 €	23,51 €	0,25 €
■ Laser	44,808 €	32,11 €	0,14 €
■ Plasma	35,298 €	26,47 €	0,21 €

Figure 13. Cost comparison

5 Conclusion

The comparative study conducted on the techno-economic aspects of metal sheet cutting technologies—plasma, oxy-fuel, and laser—demonstrates a nuanced landscape where cost-effectiveness is not solely determined by operational or cutting costs. Instead, the analysis reveals that the efficiencies of these technologies are profoundly influenced by their performance metrics such as cutting speed, precision, and the quality of the cut.

While laser technology presents the highest operational and total cutting costs, at €44,408 per hour and €32.11 respectively, it simultaneously offers the lowest cost per meter of cut at €0.14. This stark contrast is primarily due to its superior cutting distance efficiency and higher precision, which significantly reduces waste and increases productivity. Despite its higher initial costs, the laser's ability to cut twice as many parts as the competing technologies within similar time frames, coupled with enhanced accuracy and better surface finish, arguably offsets these expenses by adding substantial value to the end products.

Conversely, while plasma and oxy-fuel technologies feature lower hourly operational costs, at €35,298 and €31,346 respectively, they do not match the laser in terms of cost-efficiency per meter of cut or output quality. Plasma achieves a moderate cost per meter of €0.21, and oxy-fuel, despite being the least expensive per hour of operation, results in the highest cost per meter of cut at €0.25. The inefficiencies of oxy-fuel, characterized by its slower cutting speeds and lower precision, underline its limitations in contexts where quality and speed are prioritized.

Ultimately, this research supports the hypothesis that modern 30kW lasers, by virtue of their enhanced capabilities and operational efficiencies, provide a more economically viable solution for cutting metal sheets compared to traditional plasma and oxy-fuel methods. This conclusion is underpinned by the laser's ability to achieve lower costs per meter of cut, better surface quality, and higher part output, which are critical factors for industries seeking to optimize production and reduce waste. The study not only affirms the economic potential of 30kW laser technology as a preferable alternative for metal sheet cutting but also highlights the importance of considering comprehensive cost metrics and productivity outcomes in the decision-making process within the metal fabrication industry.

The findings of this study, while clearly demonstrating the economic advantages of 30kW laser technology for metal sheet cutting, are specific to the operational settings and material thickness (25 mm S355J2) observed in Estonia. These results, although indicative of broader trends, may vary depending on local conditions, material specifications, and technological availability. The cost efficiencies and productivity gains reported here reflect a particular scenario that may not universally apply but should provide a similar comparative outcome in analogous settings.

Further research could beneficially extend these findings by exploring a broader range of material thicknesses and assessing the impact of even more powerful technologies, such as the emerging 60kW lasers. Such studies would provide a deeper understanding of the scalability and adaptability of laser technology across different industrial applications and material types. Investigating these higher-powered lasers could reveal additional efficiencies and thresholds where laser technology not only matches but significantly surpasses traditional methods like plasma and oxy-fuel in both economic and operational dimensions.

SUMMARY

This thesis conducts a detailed techno-economic analysis comparing three prevalent metal sheet cutting technologies—plasma, oxy-fuel, and laser—within the operational context of TerasToorik AS, a company specializing in metal fabrication. The research is driven by the manufacturing sector's ongoing quest to optimize cost and operational efficiency, considering the crucial role of metal cutting technologies in production processes.

The primary aim of this thesis was to evaluate the technological and economic performance of laser, plasma, and oxy-fuel cutting methods to determine the most cost-effective and efficient option for TerasToorik AS. This objective was pursued through a systematic methodology that included the selection of cutting machines, the definition of comparative parameters for each technology, and the collection of empirical data from TerasToorik AS. The analysis focused on direct operational costs, including consumables, labor, and maintenance, alongside performance metrics such as cutting speed, precision, and quality of cuts.

The findings revealed that while laser technology incurs higher operational and cutting costs per hour (€44,408 and €32.11, respectively), it offers the lowest cost per meter of cut (€0.14). This is attributed to the laser's superior cutting distance efficiency and precision, which significantly reduce waste and enhance productivity. In contrast, plasma and oxy-fuel technologies, despite their lower hourly operational costs (€35,298 for plasma and €31,346 for oxy-fuel), do not achieve the same level of cost efficiency per meter of cut or output quality, with costs per meter of €0.21 and €0.25, respectively.

The thesis substantiates the hypothesis that 30kW lasers are more economically viable for cutting metal sheets compared to traditional plasma and oxy-fuel methods, particularly in settings like TerasToorik AS where precision and efficiency are paramount. The advanced capabilities of modern laser systems, such as reduced consumable use and enhanced cutting precision, make them a compelling choice despite their higher initial costs.

KOKKUVÕTE

Käesolevas lõputöös tehakse üksikasjalik tehnomajanduslik analüüs, milles võrreldakse kolme levinud metalllistide lõikamise tehnoloogiat – plasma-, gaasi- ja laseri – metallide valmistamisele spetsialiseerunud ettevõtte TerasToorik AS alusel. Uurimistöö on ajendatud tootmissektori jätkuvatest püüdlustest optimeerida kulusid ja tegevustõhusust, arvestades metalli lõikamise tehnoloogiate üliolulist rolli tootmisprotsessides.

Lõputöö esmane eesmärk oli hinnata laser-, plasma- ja gaasilõikamismeetodite tehnoloogilisi ja majanduslikke näitajaid, et teha kindlaks TerasToorik AS-ile kõige efektiivsem (sealhulgas kuluefektiivsem) variant. Seda eesmärki saavutatakse süstemaatilise metoodika abil, mis hõlmab lõikemasinate valikut, iga tehnoloogia võrdlevate parameetrite määratlemist ja empiiriliste andmete kogumist TerasToorik AS-ist. Analüüs keskendus otsestele tegevuskuludele, sealhulgas kulumaterjalidele, tööjõule ja hooldusele, ning jõudlusnäitajatele, nagu lõikekiirus, täpsus ja lõigete kvaliteet.

Tulemustest selgus, et kuigi lasertehnoloogiaga kaasnevad suuremad töö- ja lõikamiskulud tunnis (vastavalt 44 408 eurot ja 32,11 eurot), pakub see kõige madalamat kulu ühe lõikemeetri kohta (0,14 eurot). Selle põhjuseks on laseri ülim lõikekauguse tõhusus ja täpsus, mis vähendab oluliselt materjaliraiskamist ja suurendab tootlikkust. Seevastu plasma- ja gaasitehnoloogiad, vaatamata nende madalamatele tunnikuludele (35 298 eurot plasma ja 31 346 eurot gaasi puhul), ei saavuta sama kulutõhususe taset lõike või väljundkvaliteedi meetri kohta, kusjuures kulud meeter vastavalt 0,21 eurot ja 0,25 eurot.

Lõputöös uurimises püstitatud hüpotees, et 30 kW laserid on metallilehtede lõikamiseks majanduslikult tasuvamad, võrreldes traditsiooniliste plasma- ja gaasi meetoditega, eriti sellistes seadetes nagu TerasToorik AS, kus täpsus ja tõhusus on ülitähtsad, on kinnitatud. Kaasaegsete lasersüsteemide täiustatud võimalused, nagu kulumaterjalide vähenemine ja suurem lõikamise täpsus, muudavad need vaatamata nende suurematele algkuludele kaalukaks valikuks.

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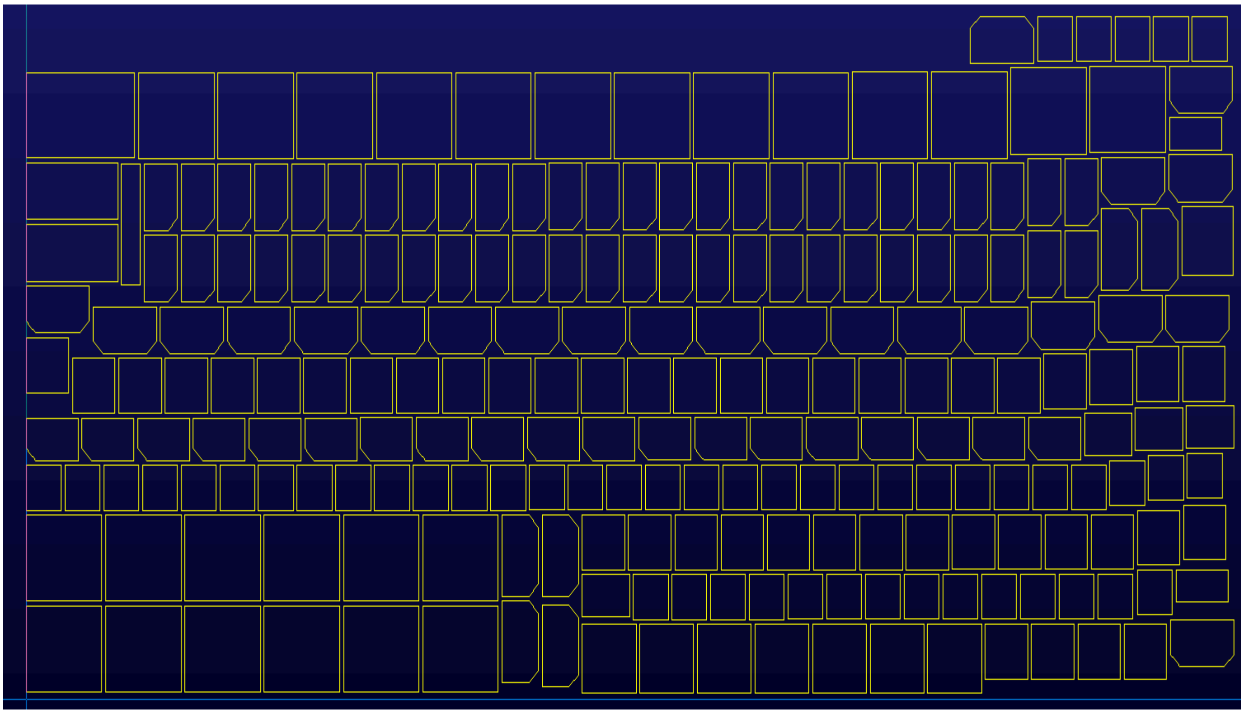
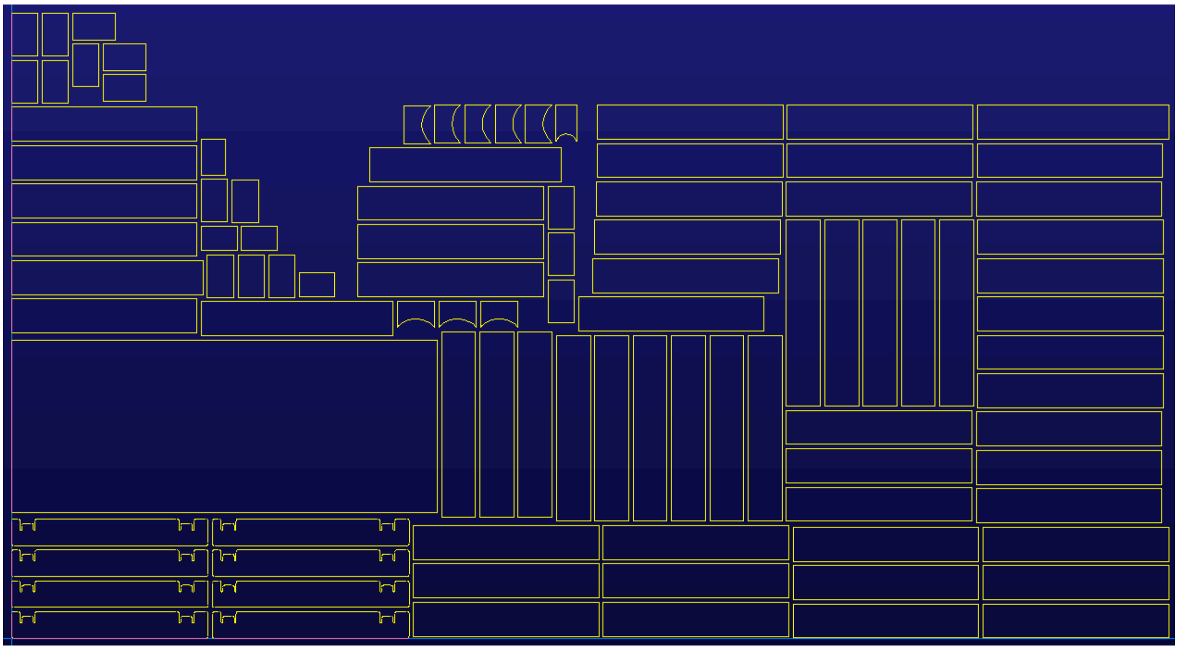
APPENDICES

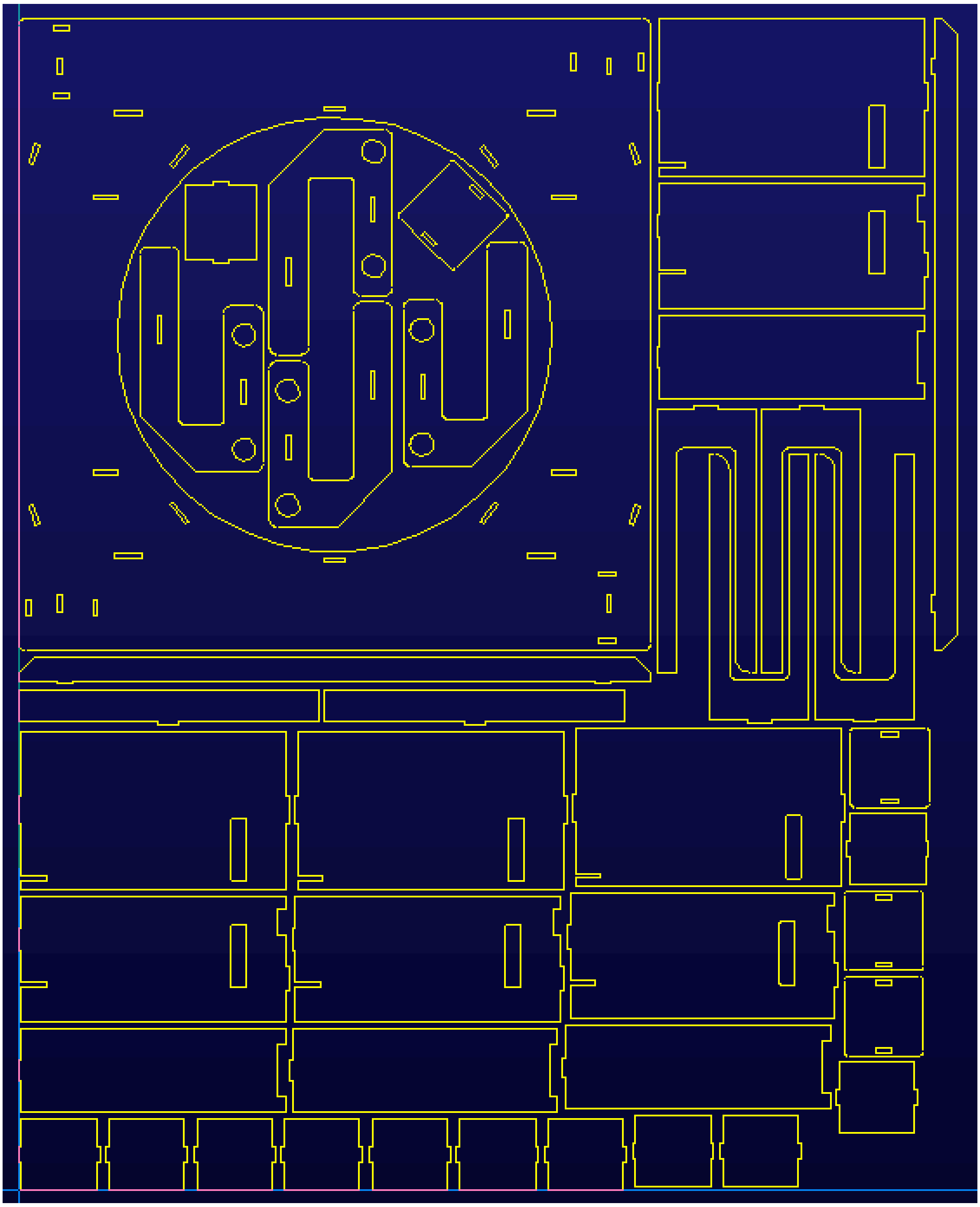
Appendix 1 Nesting of parts on 5 mm thick metal sheet



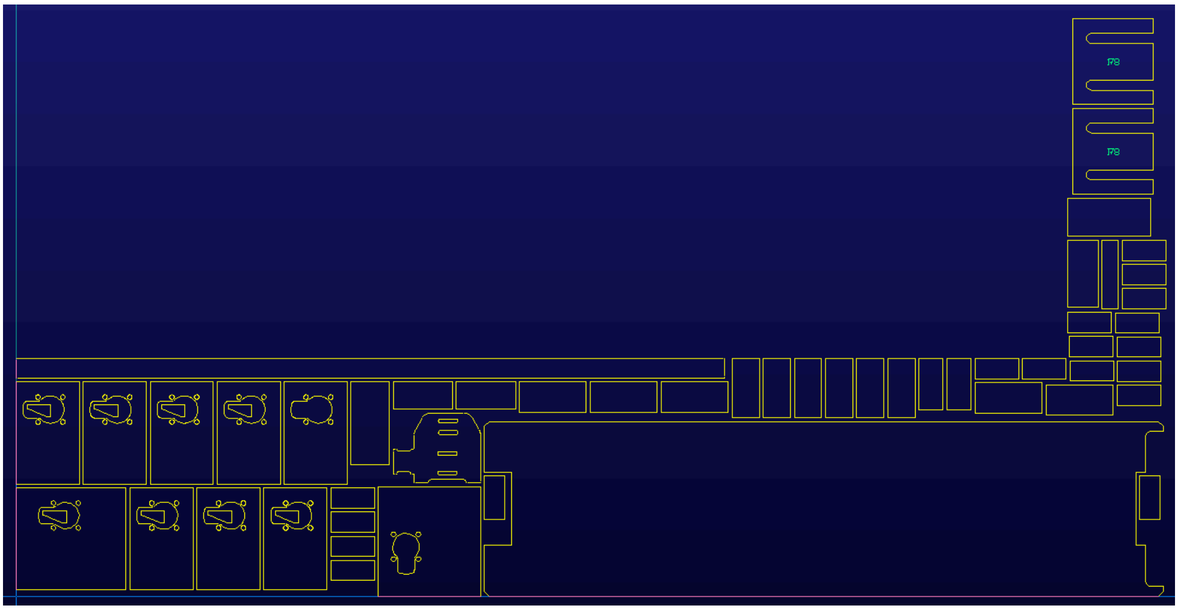
Appendix 2 Nesting of parts on 5 mm thick metal sheet



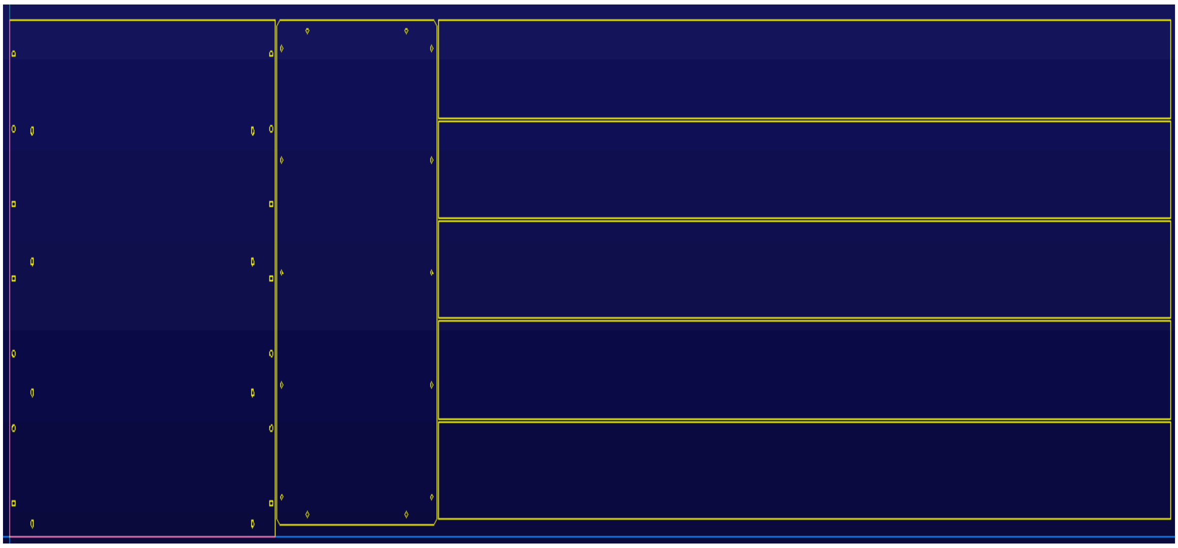
Appendix 3 Nesting of parts on 5 mm thick metal sheet



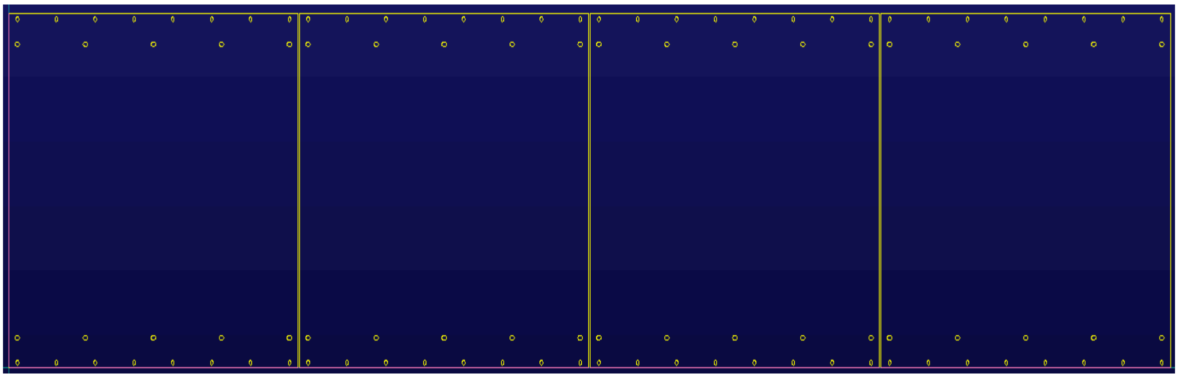
Appendix 4 Nesting of parts on 5 mm thick metal sheet



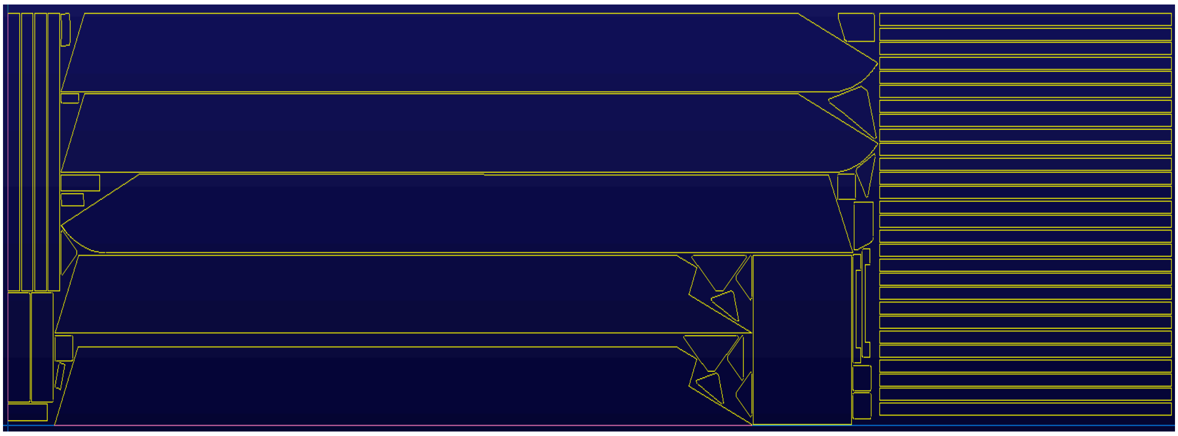
Appendix 5 Nesting of parts on 5 mm thick metal sheet



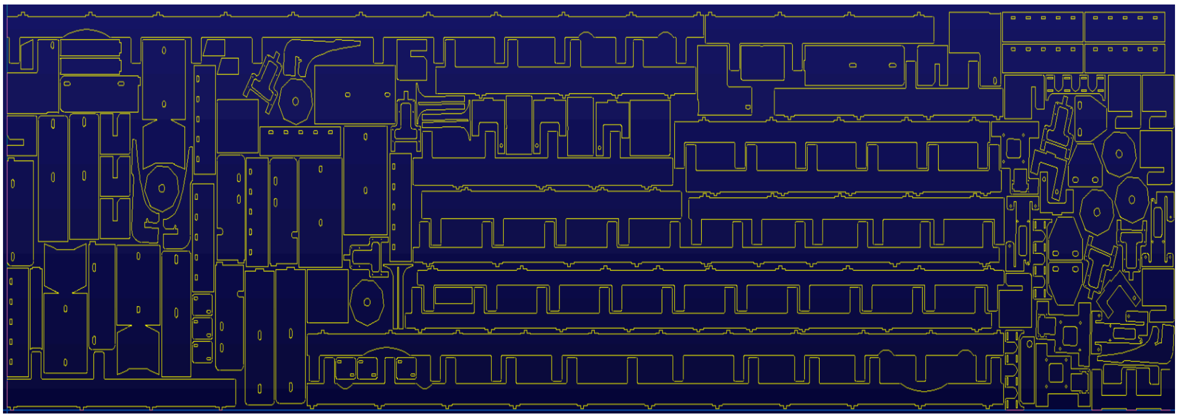
Appendix 6 Nesting of parts on 5 mm thick metal sheet



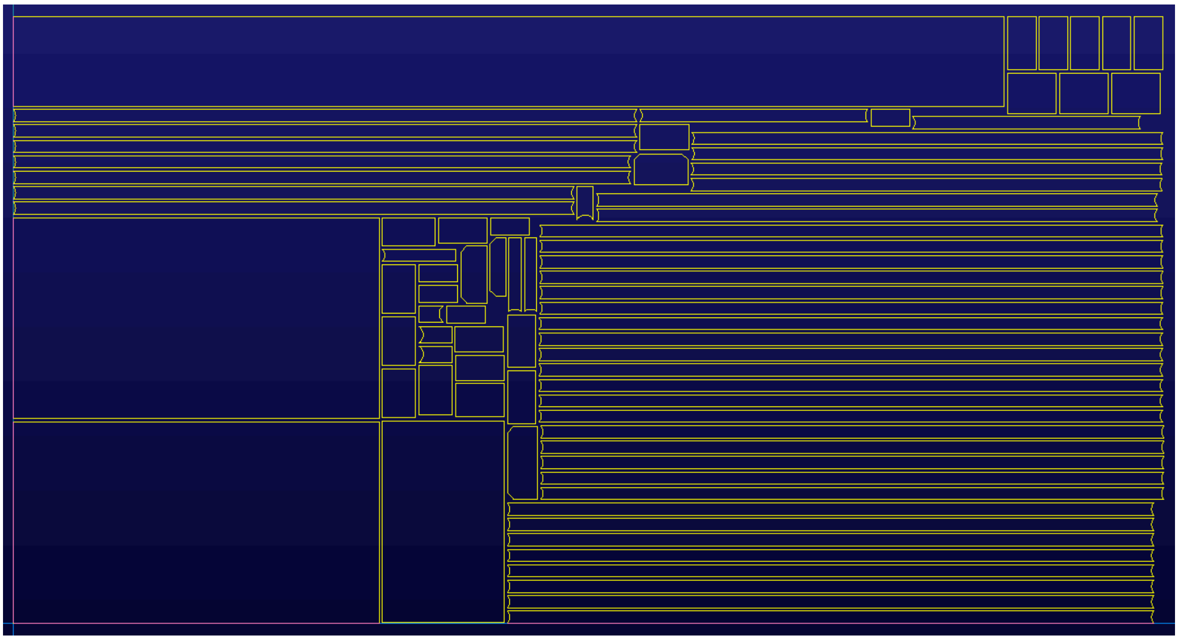
Appendix 7 Nesting of parts on 5 mm thick metal sheet



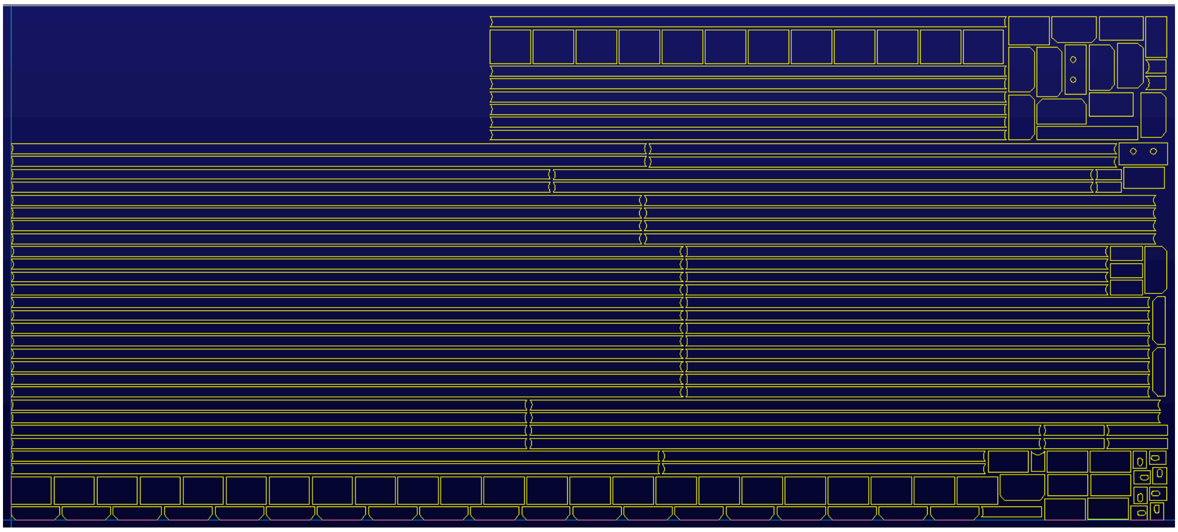
Appendix 8 Nesting of parts on 5 mm thick metal sheet



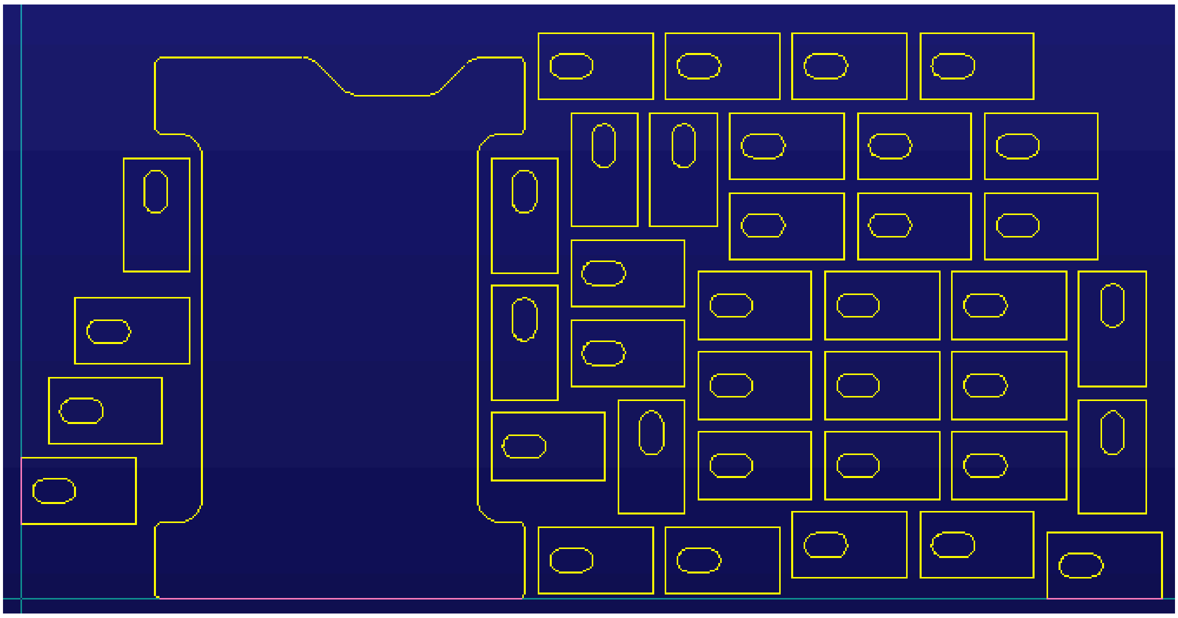
Appendix 9 Nesting of parts on 5 mm thick metal sheet



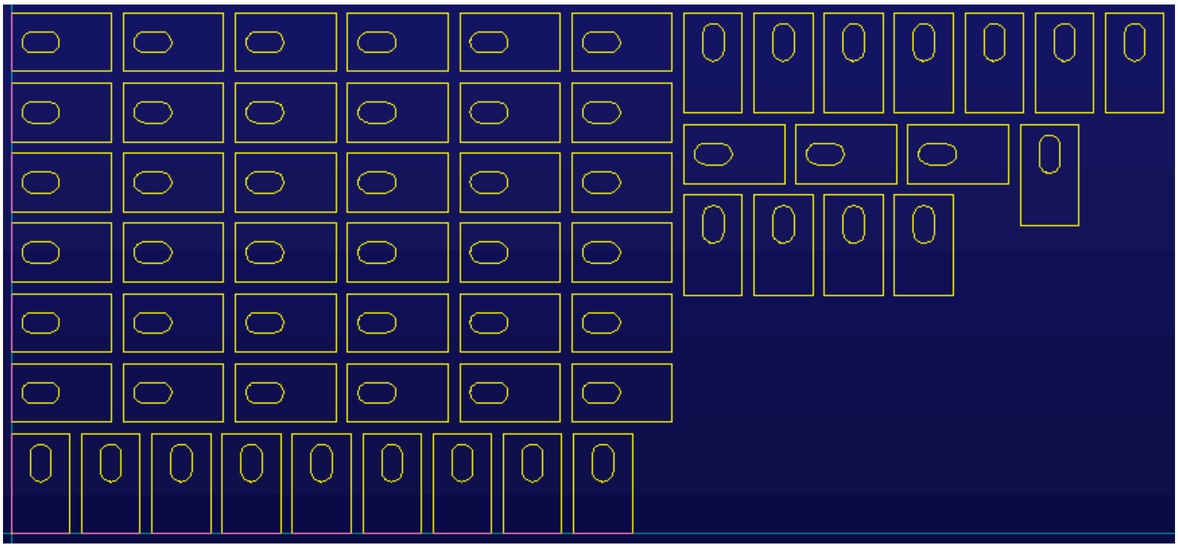
Appendix 10 Nesting of parts on 5 mm thick metal sheet



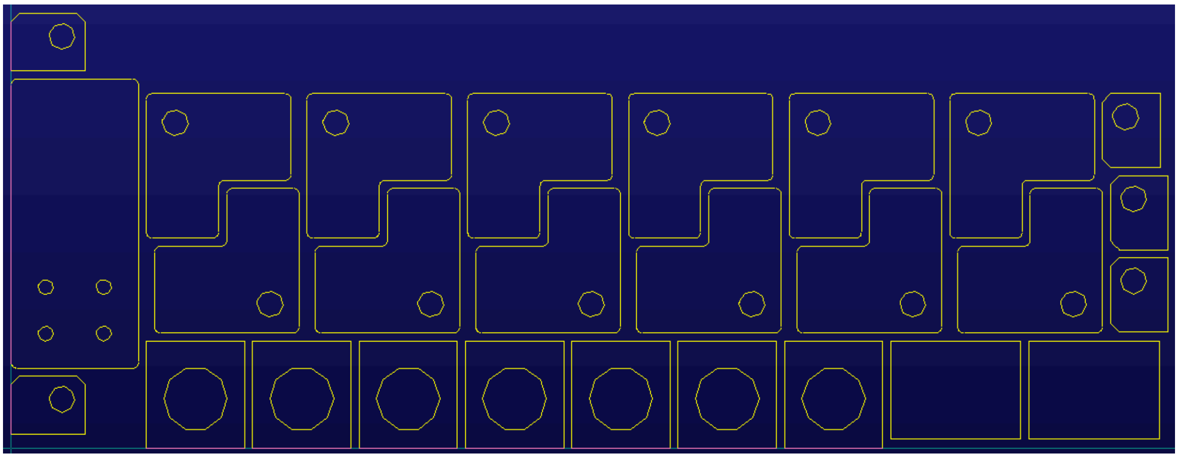
Appendix 11 Nesting of parts on 25 mm thick metal sheet



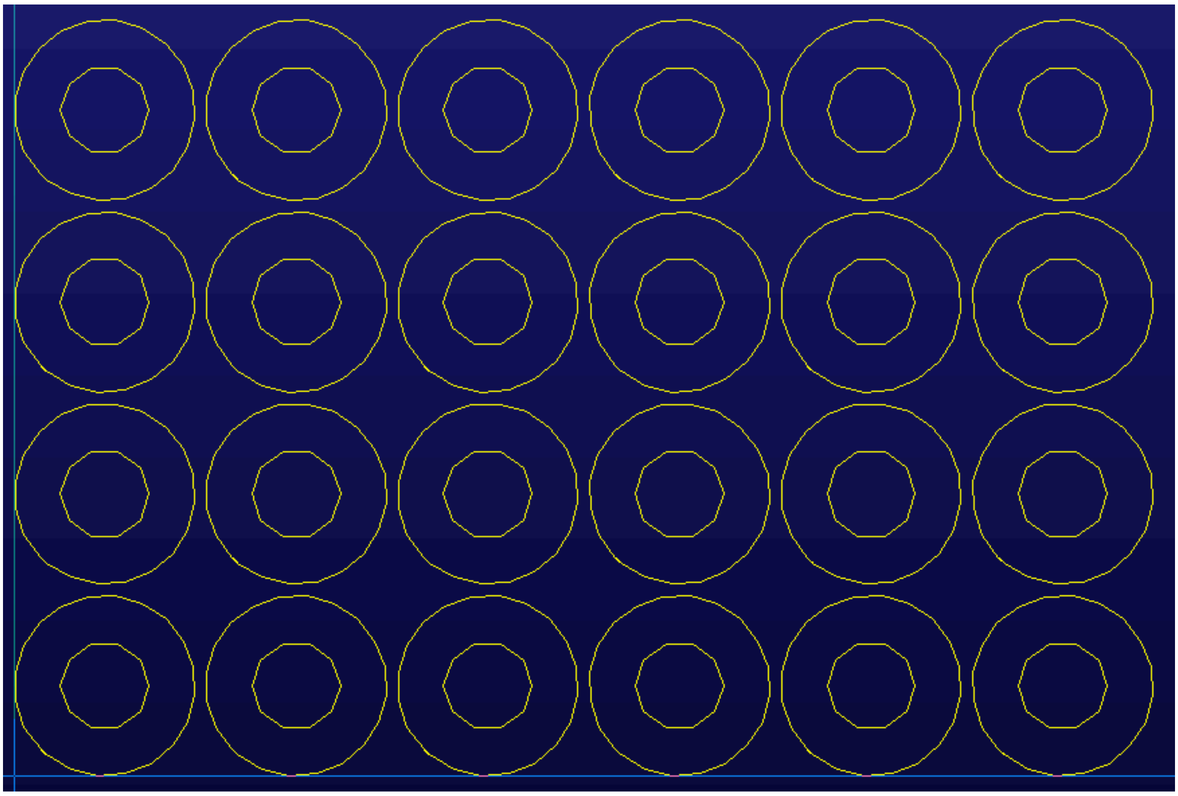
Appendix 12 Nesting of parts on 25 mm thick metal sheet



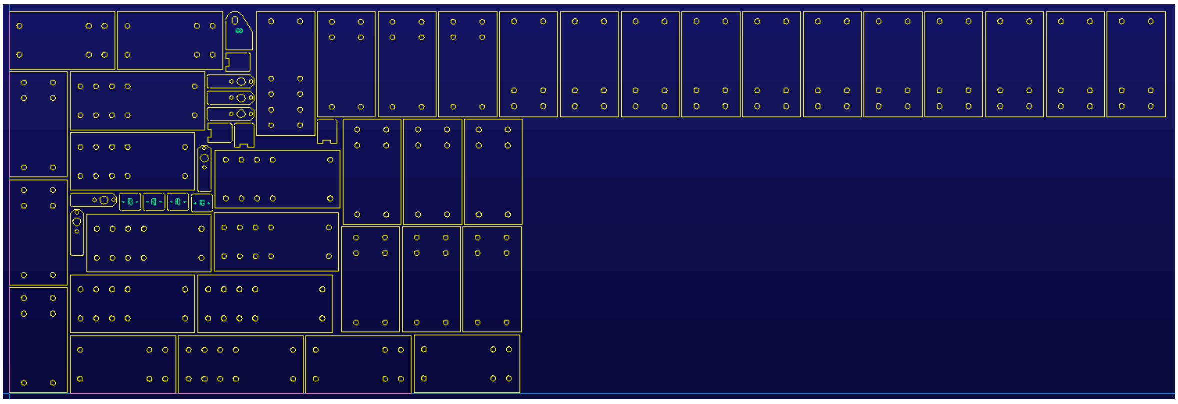
Appendix 13 Nesting of parts on 25 mm thick metal sheet



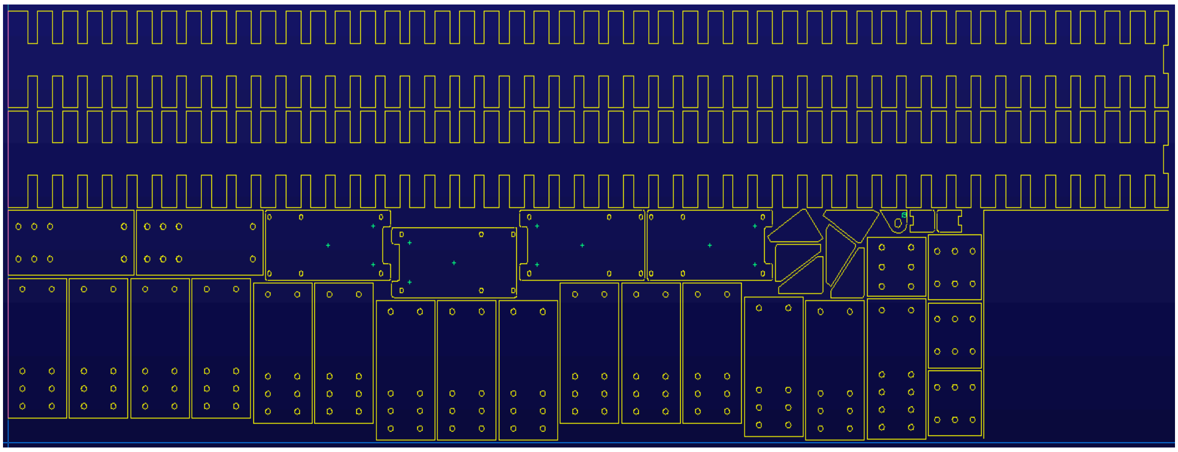
Appendix 14 Nesting of parts on 25 mm thick metal sheet



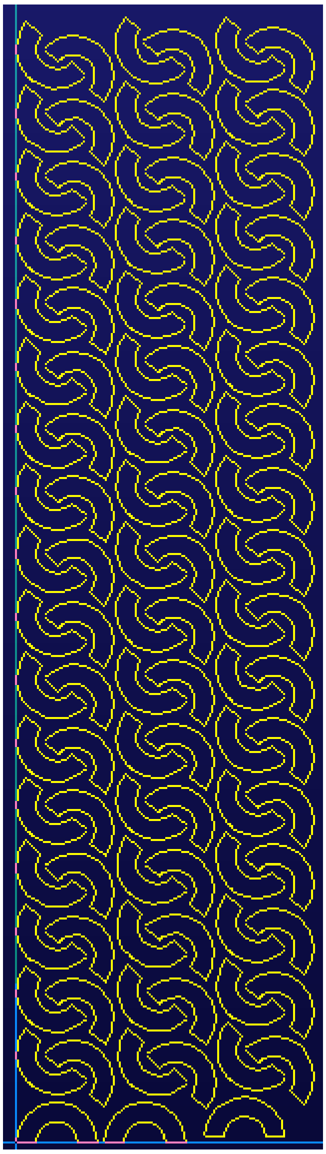
Appendix 15 Nesting of parts on 25 mm thick metal sheet



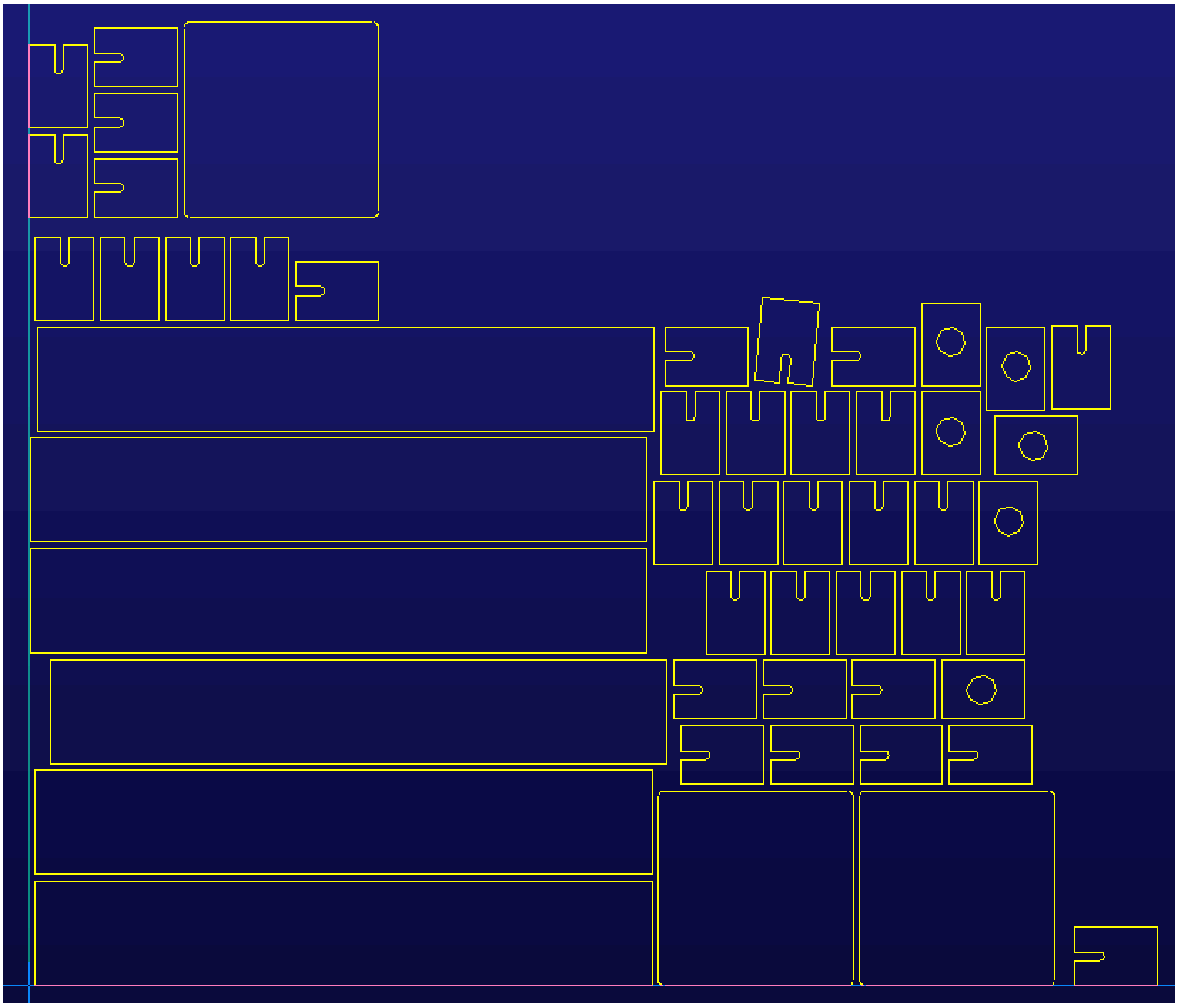
Appendix 16 Nesting of parts on 25 mm thick metal sheet



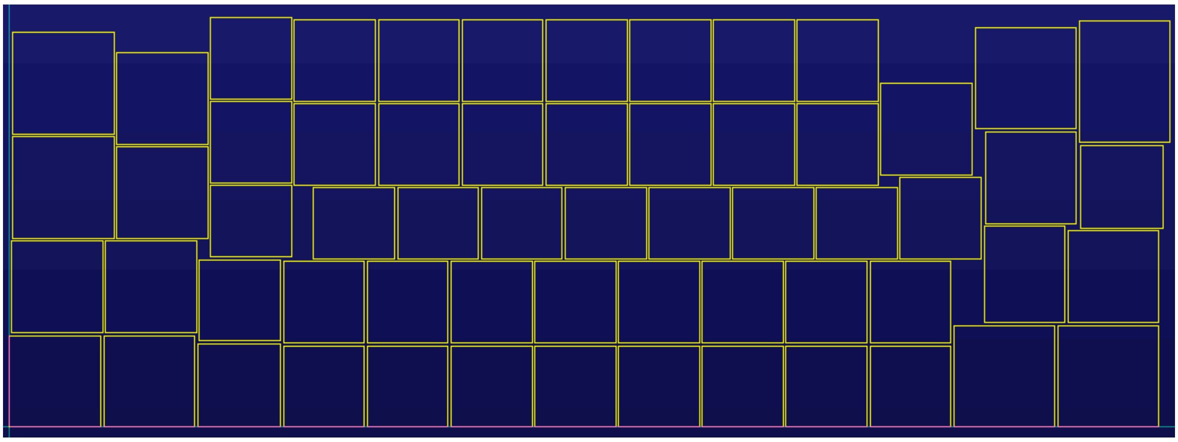
Appendix 17 Nesting of parts on 25 mm thick metal sheet



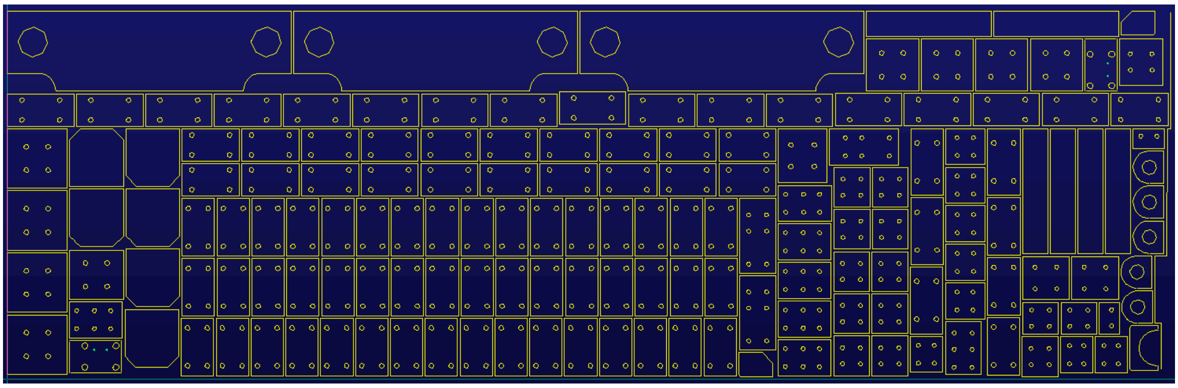
Appendix 18 Nesting of parts on 25 mm thick metal sheet



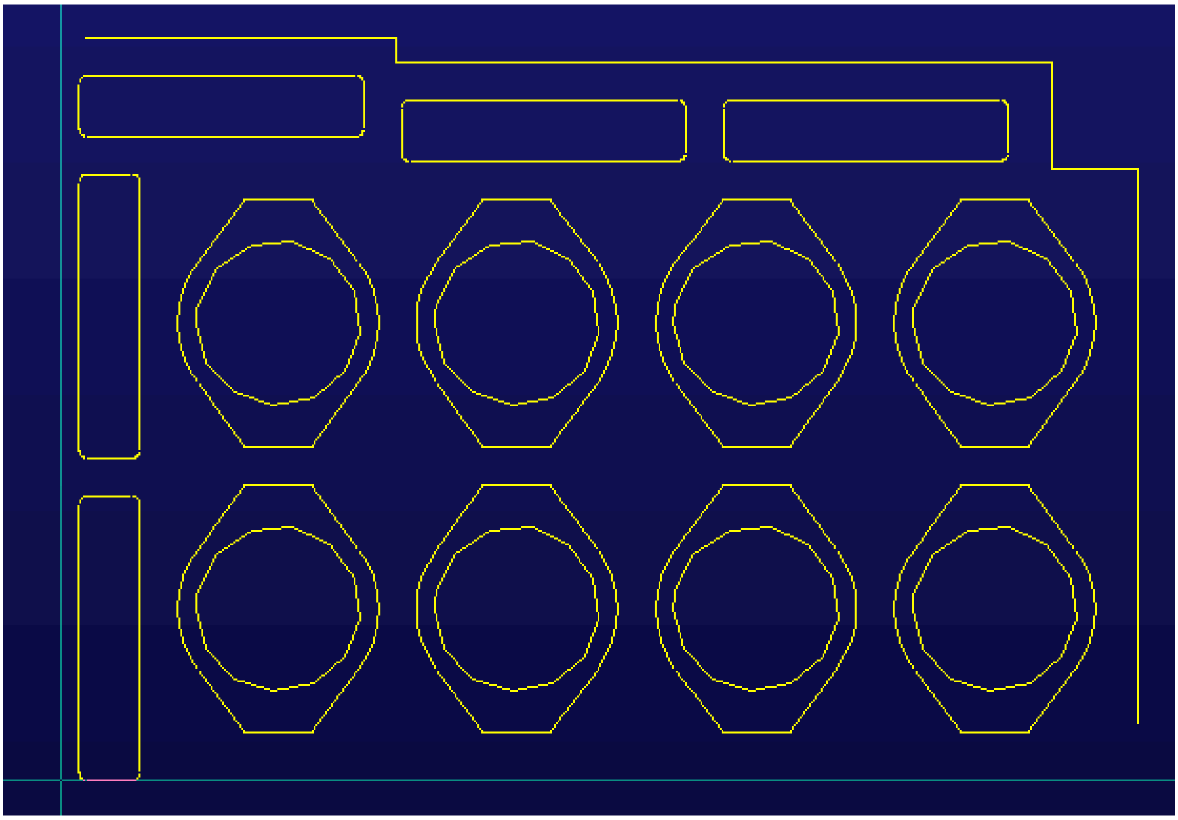
Appendix 19 Nesting of parts on 25 mm thick metal sheet



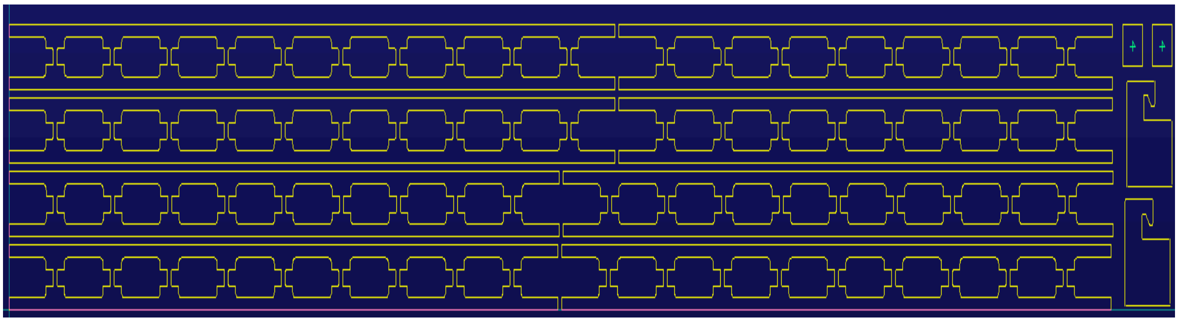
Appendix 20 Nesting of parts on 25 mm thick metal sheet



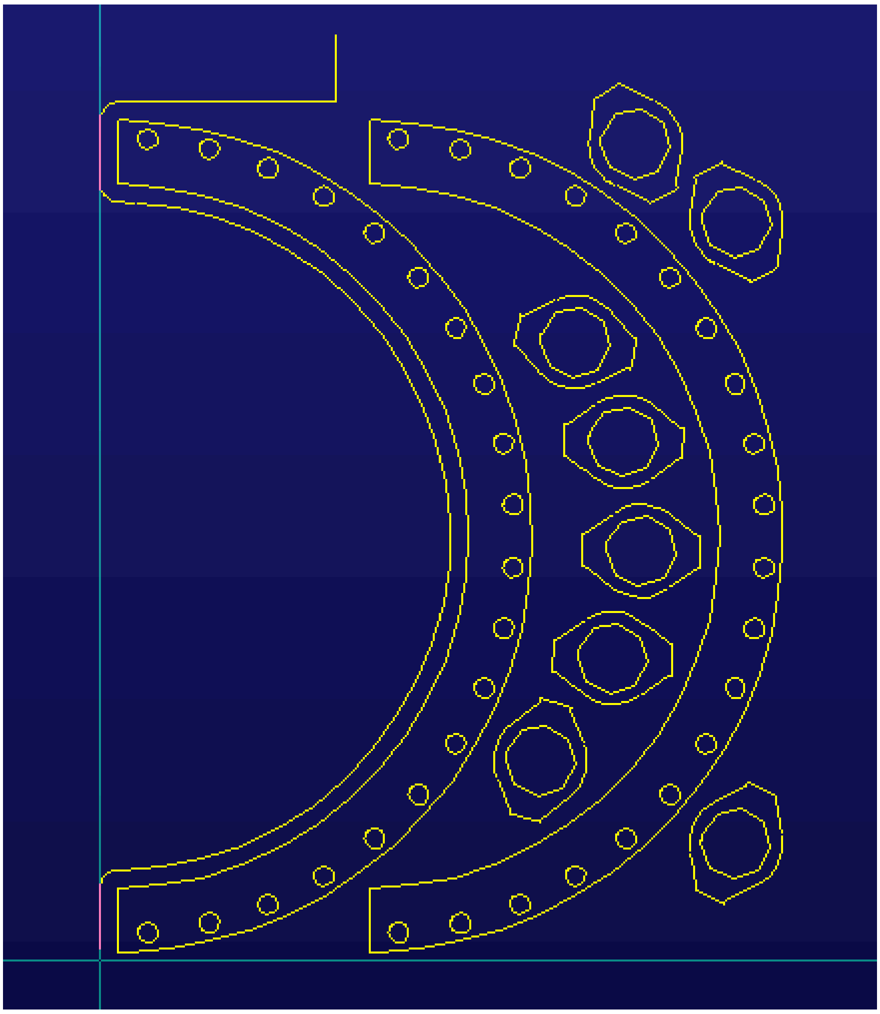
Appendix 21 Nesting of parts on 40 mm thick metal sheet



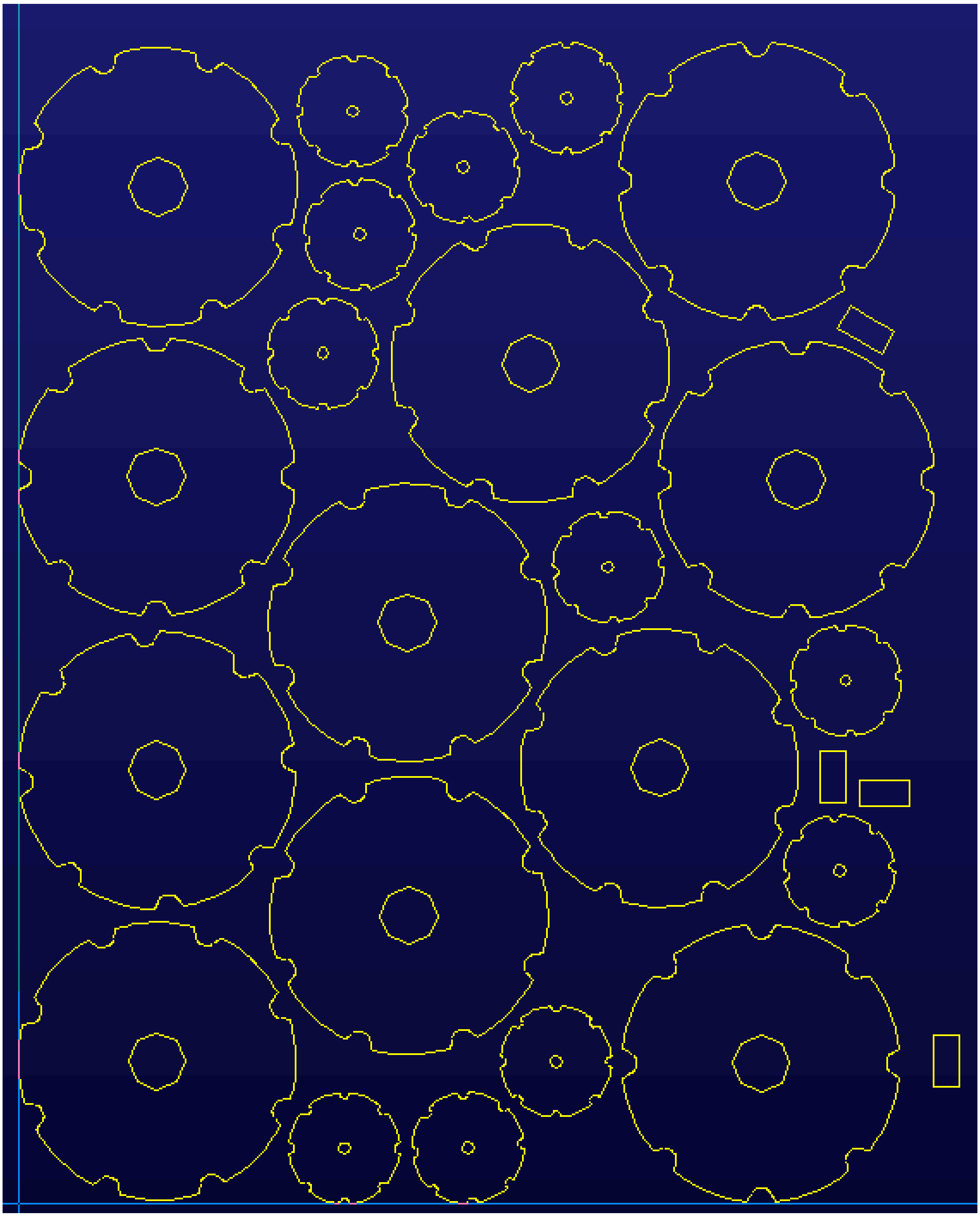
Appendix 22 Nesting of parts on 40 mm thick metal sheet



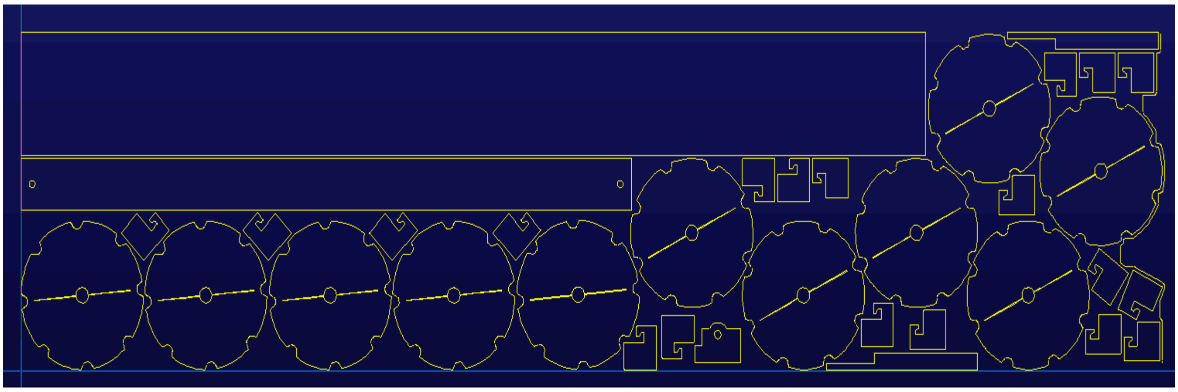
Appendix 23 Nesting of parts on 40 mm thick metal sheet



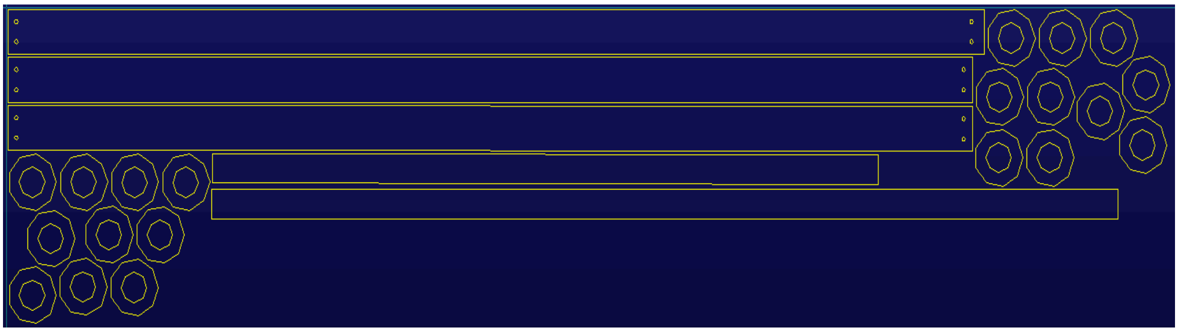
Appendix 24 Nesting of parts on 40 mm thick metal sheet



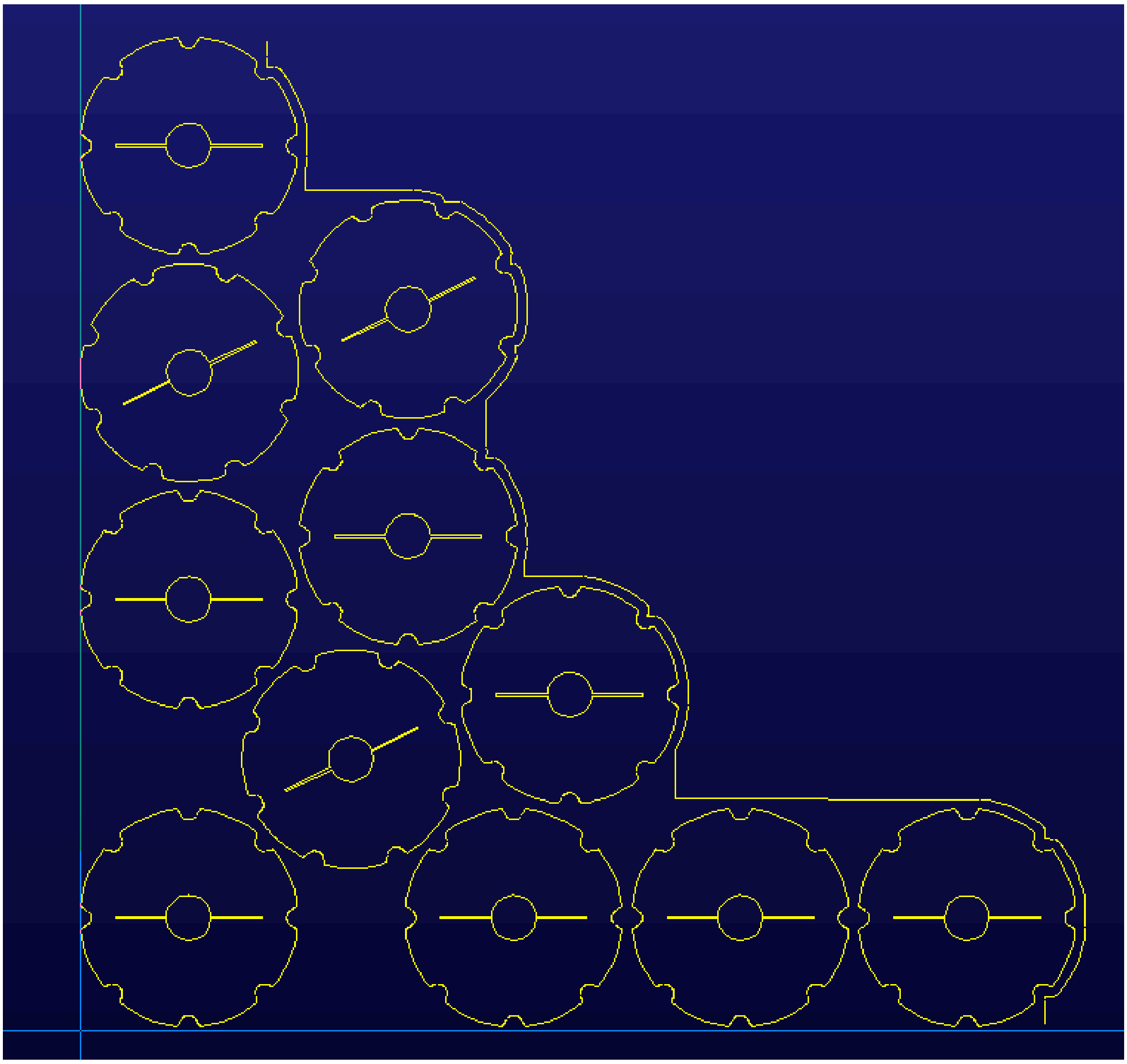
Appendix 25 Nesting of parts on 40 mm thick metal sheet



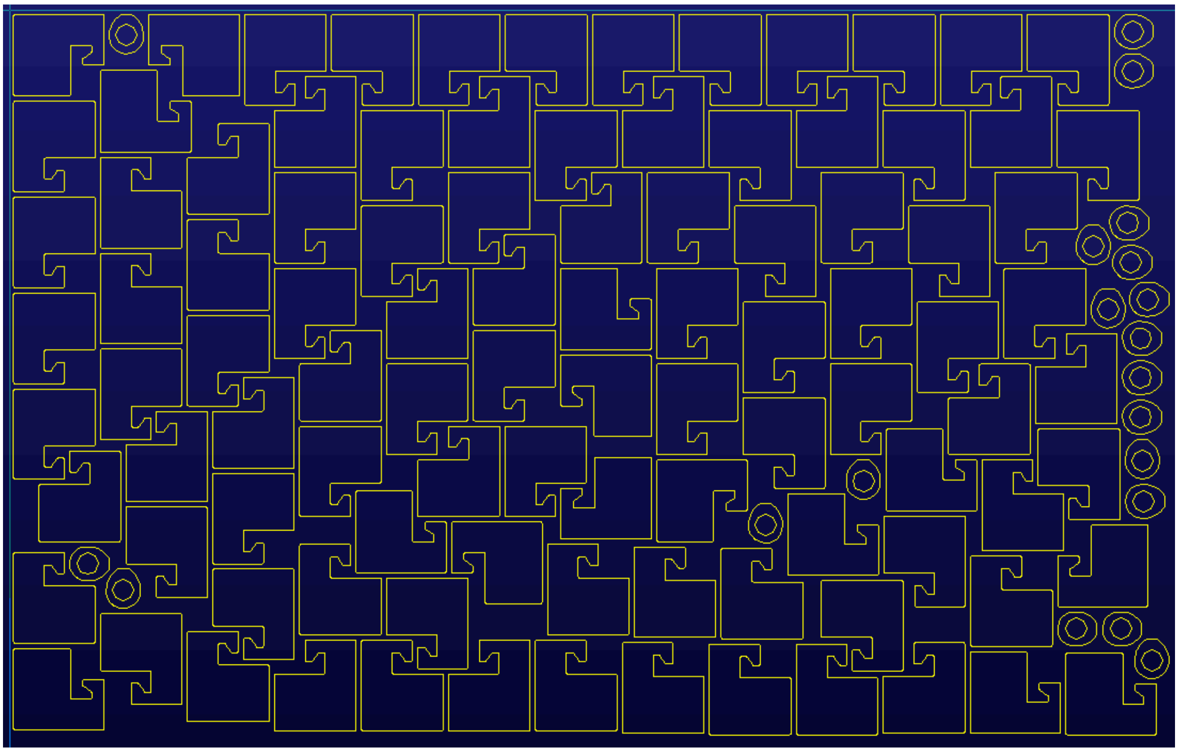
Appendix 26 Nesting of parts on 40 mm thick metal sheet



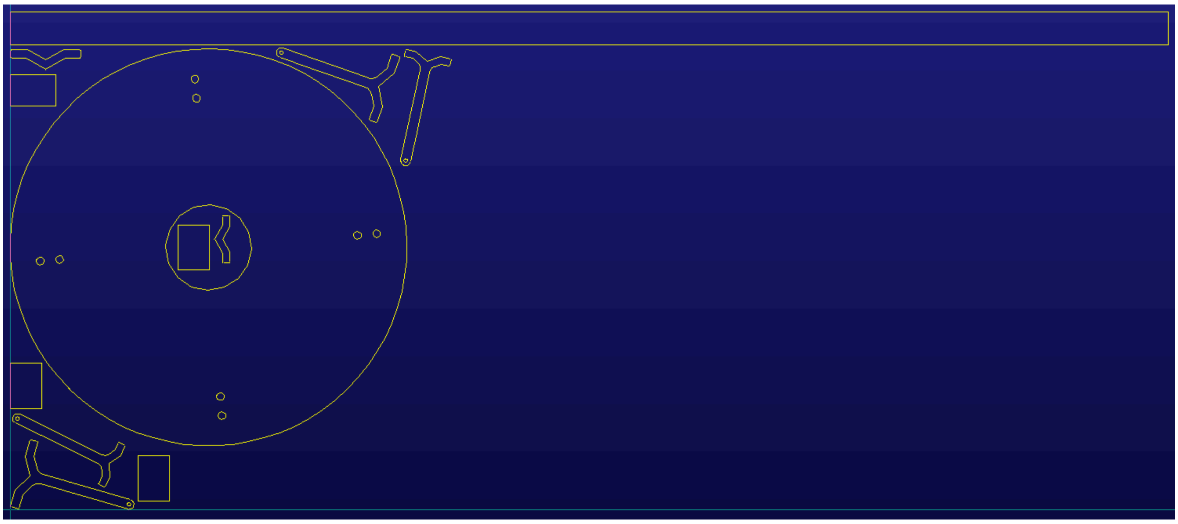
Appendix 27 Nesting of parts on 40 mm thick metal sheet



Appendix 28 Nesting of parts on 40 mm thick metal sheet



Appendix 29 Nesting of parts on 40 mm thick metal sheet



Appendix 30 Nesting of parts on 40 mm thick metal sheet