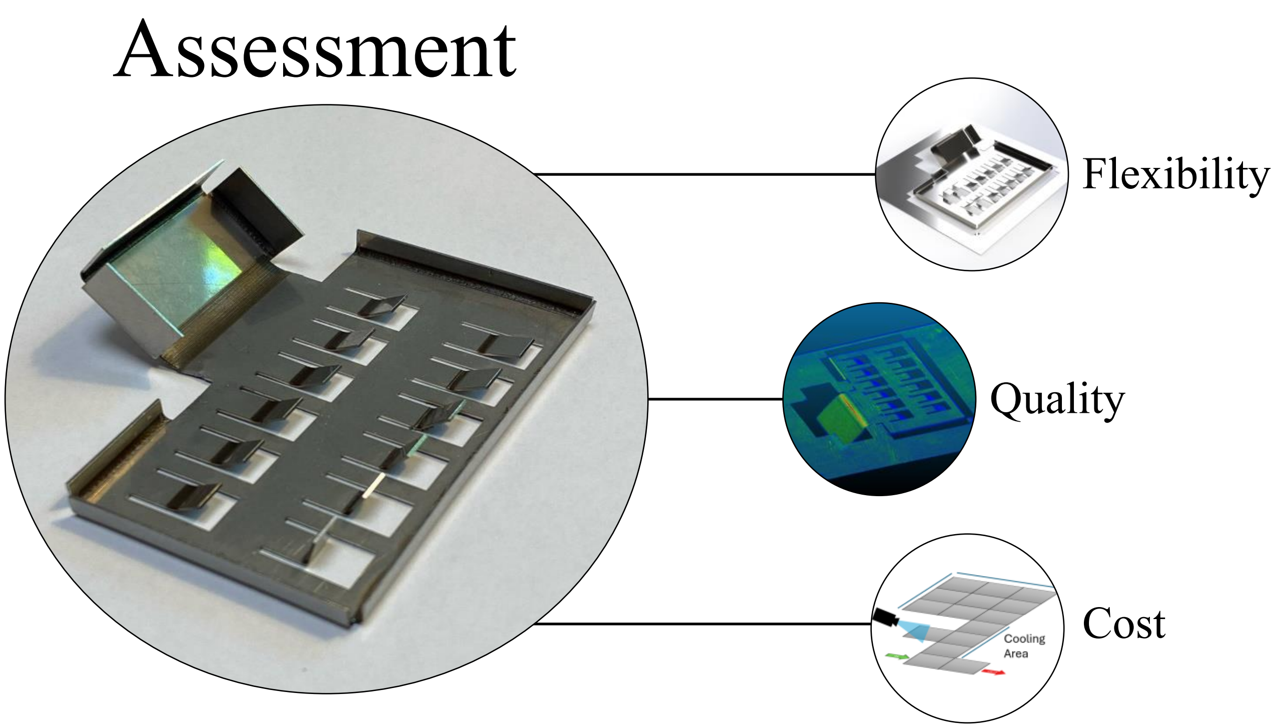
Aalborg University

Department of Materials & Production

Manufacturing Technology

Master Thesis

Assessing Magnetic Levitation for Flexible Laser Processing in Low-Volume Sheet Metal Manufacturing



AALBORG UNIVERSITY

AALBORG UNIVERSITY
STUDENT REPORT

Manufacturing Technology / Virksomhedsteknologi
Aalborg University
http://www.mp.aau.dk

Title:
Assessing Magnetic Levitation for Flexible Laser Processing in Low-Volume Sheet Metal Manufacturing

Theme:
Master Thesis

Project Period:
Feb. 2025 - May. 2025

Project Group:
Group 5

Participants:
Mads Holm Andersen
Mads Augustinus Frøhlich

Supervisor:
Morten Kristiansen

Number of Pages: 74

Date of Completion: 30. May. 2025

Abstract

This master's thesis investigates the potential of magnetic levitation in laser-based processing, focusing on improving flexibility, quality, and cost-efficiency for low-volume production and rapid prototyping. As demand for customisation and sustainable manufacturing increases, the study explores how component-level design changes can influence system performance across these aforementioned objectives.

A two-stage literature study identifies a gap in the industrial adoption of laser forming, which remains underutilised compared to laser cutting, welding and engraving. To address this, engineering specifications based on industry stakeholder interviews and literature are defined, and two fixture approaches are proposed. Approach Two, involving a cutout template, is selected for its adaptability and simplicity.

The magnetic levitation system is developed using empirical parameters and assessed against the relevant engineering requirements. Results show that the desired flexibility is achieved, and the system, when scaled, can meet low-volume order sizes. Although angle accuracy deviates from the targeted value due to open-loop control, the process allows for salvage of under-formed parts, reducing the cost of poor quality (hidden and visible cost stemming from poor quality). Cost analysis confirms that magnetic levitation is a viable option for low-volume and prototyping applications, offering consistent unit costs without tooling expenses.

In conclusion, magnetic levitation in laser-based processing shows strong industrial relevance and presents a promising foundation for an integrated, "all-in-one" laser processing platform for the sheet metal industry.

Resume

Dette speciale undersøger potentialet ved at anvende magnetisk levitation i laserbaserede produktionssystemer med særligt fokus på at forbedre fleksibilitet, kvalitet og omkostningseffektivitet i lavvolumenproduktion og hurtig prototype fremstilling. Det stigende behov for kundetilpasset og bæredygtig produktion har synliggjort begrænsningerne ved konventionelle plade metals fremstillingsmetoder, især når der kræves høj variation og korte leveringstider. Specialet undersøger, hvordan ændringer på komponentniveau kan påvirke systemets ydeevne inden for de tre definerede målsætninger.

Gennem et to-trins litteraturstudie identificeres en industriel mangel på integreret laserformning, som i modsætning til laserskæring, -svejsning og -gravering endnu ikke er udbredt i pladeindustrien. Ingeniørmæssige krav baseret på interviews med interessenter og litteratur fastlægges, og to tilgange for fiksturdesign analyseres. Tilgang to, som baseres på en præskåret skabelon, vælges grundet dens enkelhed og evne til at håndtere produktvariationer uden komplekse mekaniske justeringer.
Produktionssystemet designes ud fra et planarmotorprincip, der muliggør kontaktløs bevægelse med seks frihedsgrader. Procesparametre for laserformning fastlægges empirisk via temperaturgradientmekanismen, og et testemne med industrielt inspirerede funktioner fremstilles for at evaluere systemets egenskaber. Resultaterne viser, at systemet opnår den ønskede fleksibilitet og, ved opskalering, har potentiale til at håndtere lavvolumenordre. Selvom nøjagtigheden af bukke vinklerne ligger uden for tolerancegrænserne grundet åben sløjfekontrol, muliggør systemets iterative natur delvis genanvendelse af underformede emner, hvilket reducerer spild og omkostningerne ved dårlig kvalitet.
En økonomisk vurdering viser, at systemet er konkurrencedygtigt i lavvolume produktion, da enhedsomkostningerne forbliver konstante og ikke påvirkes af værktøjsomkostninger. På sigt anbefales integration af et lukket feedback-system baseret på 3D-scanning og punktskyanalyse for at forbedre bøjeprecisionen og kvaliteten.

Samlet set demonstrerer specialet, at et magnetisk levitationsbaseret lasersystem udgør en lovende platform for fremtidens fleksible og bæredygtige produktion inden for laser pladebearbejdning. Systemet adresserer udfordringer i lavvolumenproduktion og fremstilling af prototyper og kombinerer høj produktfleksibilitet med potentiale for omkostningseffektivitet. På baggrund af resultaterne vurderes det, at systemet har industriel relevans og kan videreudvikles som et integreret "all-in-one"-lasersystem.

Table of Contents

Preface

This master's thesis is submitted by 4th semester Master's students in Manufacturing Technology at Aalborg University (AAU) as part of the requirements for obtaining the degree Master of Science in Engineering. The thesis is written using LaTeX and follows the Vancouver referencing style. Unless otherwise stated, all figures and tables are produced by the project group.

The thesis reflects the students' ability to acquire and apply new knowledge to address a complex engineering challenge within the field of manufacturing technology. Emphasis has been placed on demonstrating both scientific and engineering competencies through systematic analysis, experimental investigation, and critical evaluation. The project has been carried out independently, with the aim of contributing to current developments in advanced manufacturing systems.

The objective of this study group is to explore and assess the potential of a novel laser processing approach based on magnetic levitation for workpiece manipulation. The research aims to understand the technical and practical requirements for developing such a system, and to evaluate its competitiveness relative to conventional production methods. Furthermore, the project investigates cost-related implications and performance metrics, with a particular focus on applications in the sheet metal industry.

Generative AI (ChatGPT) has been used to refine the written content by correcting grammatical errors and improving clarity, ensuring that the thesis adheres to a professional standard while maintaining academic precision and coherence.

The study group wishes to express sincere gratitude to Georgi Nikolov, Research Assistant at the Department of Materials and Production, for his technical support regarding the laser cell and laser cutting software. We also extend our thanks to Christos Kantas, Master's student at the Department of Architecture, Design and Media Technology, for his contribution to the point cloud analysis and generation of relevant results. Appreciation is further directed to the industry representatives who provided valuable input on system requirements, and to the employees at Asetek for their assistance in manufacturing the cut templates. A special thanks goes to Torben Hyllested, Sales Engineer at Beckhoff, for providing price estimates for the magnetic levitation process system. Lastly, we thank the workshop staff at AAU for their practical support throughout the project.

Nomenclature

Abbreviations		
Abbreviation	**Description**	**Unit**
AAU	Aalborg University	
AI	Artificial Intelligence	
BM	Buckling Mechanism	
CNC	Computer Numerical Control	
CoPQ	Cost of Poor Quality	
DML	Dedicated Manufacturing Line	
DOF	Degrees of Freedom	
E	Engraving	
F	Forming	
FMS	Flexible Manufacturing System	
KPI	Key Performance Indicator	
MIG	Metal Inert Gas	
MoSCoW	Must or Should or Could or Will Not	
RANSAC	Random Sample Consensus	
R&D	Research and Development	
RMS	Reconfigurable Manufacturing System	
ROI	Return on Investment	
RSW	Resistance Spot Welding	
TGM	Temperature Gradient Mechanism	
TIG	Tungsten Inert Gas	
UM	Upsetting Mechanism	

Symbols		
Symbols	**Description**	**Unit**
d	Laser Beam Diameter	mm
D	Engraving Depth	mm
F_0	Fourier's Number	-
t	Thickness of Material, Time	mm, s
v	Laser Scan Speed	$mm\,s^{-1}$
κ	Thermal Diffusivity	$m^2\,s^{-1}$

Glossary

The following glossary provides definitions and clarifications of key terms used throughout this project.

Experimental System: Refers to the physical setup used for producing the assessment part. It consists of a single magnetic mover, one XPlanar tile, and one laser unit.

Proposed System: Denotes the conceptual production system designed for industrial scalability. It comprises multiple movers, tiles, and laser units. Two configurations are considered: a small-scale system with 15 tiles and 8 movers, and a large-scale system with 36 tiles and 25 movers.

Mag-Lev: An abbreviation for magnetic levitation. In this context, it refers to the developed magnetic levitation-based laser processing system.

Scan Line: Is defined as the path where the laser is turned on, this may also be referred to as pass or scan pass.

Low-Volume Production: Defined as a production volume of 1–10,000 units, typically characterised by short lead times and low setup costs. [44]

Medium-Volume Production: Refers to a production volume of 10,000–50,000 units, generally associated with moderate lead times and setup costs. [44]

High-Volume Production: Refers to production volumes exceeding 50,000 units, also characterised by moderate lead times and setup costs. [44]

1. Introduction

Sheet metal manufacturing is widely used in sectors such as construction, automotive, aerospace, and consumer electronics, where steel and aluminium are the most commonly used materials in the industry. The sheet metal industry is integral to modern manufacturing, supplying critical components across all these diverse sectors. However, the production of these components presents both general manufacturing challenges and sustainability concerns. [1, 45, 46] Manufacturing challenges include high tooling, equipment, and labour costs, compounded by the increasing demand for complex geometries requiring high precision and competitive production rates. [2, 3] Sustainability challenges have gained importance, driven by increasing pressure from end users, industry stakeholders, and regulatory bodies. Manufacturers are required to reduce their environmental footprint, resulting in a demand for more sustainable and high-quality production methods. [2, 3]

The industry is actively pursuing solutions to manufacturing challenges, particularly with the shift towards Industry 4.0. Traditional methods, such as sensors, power optimisation, and cost-efficient processing techniques, have addressed some of these issues. [45, 46] However, these solutions often come with environmental trade-offs or necessitate extensive research for incremental improvements. [46] This often leads to reluctance in adopting new technologies, primarily driven by the high costs associated with research and development, where the perceived incremental benefits are considered insufficient to justify the investment. As a result, a conservative mindset emerges, favouring established practices over innovation. Laser processing technologies can potentially revolutionise the sheet metal manufacturing industry by addressing several long-standing challenges related to precision, tool wear, and production flexibility. Many of the challenges faced by traditional manufacturing can be addressed through laser technology, which enables iterative processing, minimises tool wear, and enhances production flexibility. This is primarily due to its versatility, as it does not require specialised tooling for different product types. However, operational metrics, particularly in forming and welding processes, still require further optimisation to meet industrial throughput standards and ensure consistent production efficiency. While the benefits of laser processing are evident, further research is crucial for its widespread adoption and addressing the existing challenges for laser-based processing. [4] The global sheet metal market underscores the importance of this research, with the steel and aluminium sector currently valued at USD 188.31 billion as of 2023, and a compound annual growth rate of 7% forecasted. [1] These figures demonstrate the need for continued innovation to meet both economic and sustainability goals.

Sheet metals are versatile materials used in various manufacturing processes, including joining, additive manufacturing, machining, forming, and finishing. [1] Common methods include chemical etching, stamping, CNC machining, rolling, diamond drag engraving, and laser processing. [47] Laser processing, particularly for cutting, welding, and finishing, has improved efficiency, speed, and precision within the industry. [5, 6] Recent research has also explored laser forming. [4, 7] Laser forming is a contactless thermo-mechanical process that uses a defocused laser beam to induce thermal stresses in a workpiece. The process operates through three mechanisms: Temperature Gradient Mechanism (TGM), Upsetting Mechanism, and Buckling Mechanism. [7] This project focuses on TGM, where a steep thermal gradient is induced, causing the material to bend towards the laser due to thermal expansion during heating and contraction during cooling. [7]

This thesis focuses on laser processing within the thin sheet metal industry, specifically for thicknesses between 0.1 and 1 $[mm]$. It explores the integration of multiple processes into a single system, with an emphasis on laser forming, where challenges in precision and speed persist, particularly for complex geometries. Current methods often lack flexibility, necessitating innovative solutions for improved control and adaptability.

To address these challenges, a process system utilising planar motors for workpiece movement has been developed to assess if it can enhance the flexibility within the industry and resolve the aforementioned challenges. The planar motors generate a magnetic field within the tile, enabling the mover, a permanent magnet, to levitate and providing it with six degrees of freedom. [8] A demo of the combination of laser forming and engraving with the magnetic levitating table can be seen in `https://youtu.be/-STezmozQJs`:

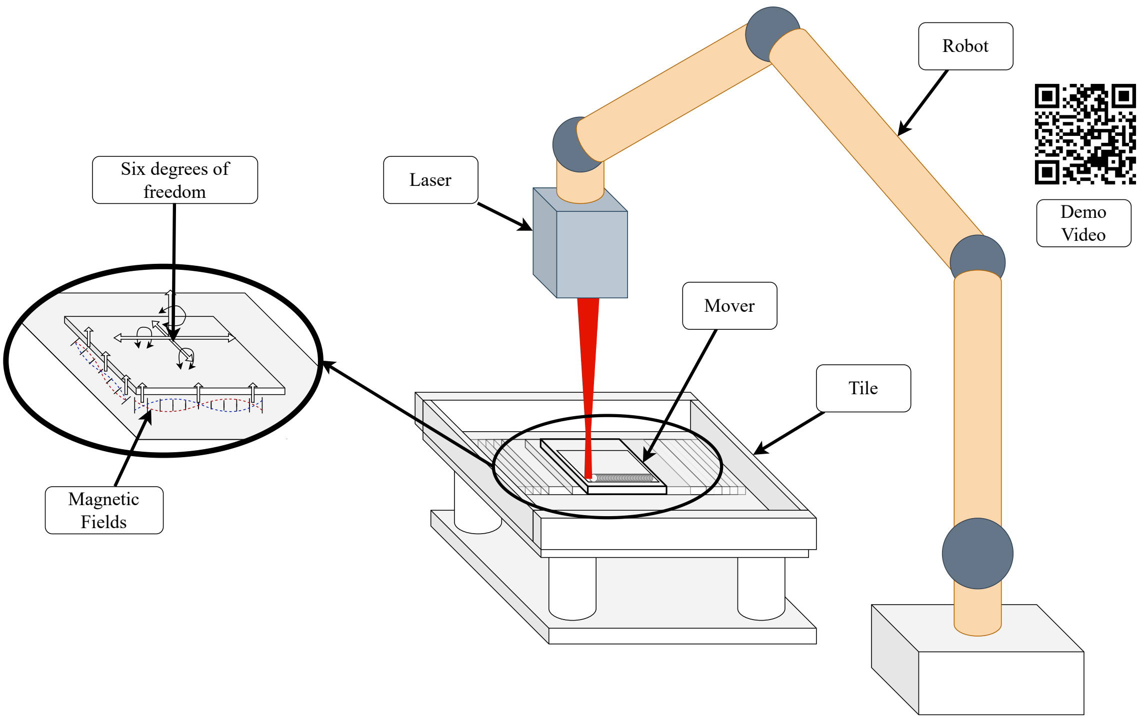


Figure 1.1: Illustration of a magnetic levitating table process system for laser processing, demonstrating workpiece manipulation. Link to demo: `https://youtu.be/-STezmozQJs`

Figure 1.1 illustrates the developed experimental laser process system, which employs a stationary laser while leveraging workpiece movement for laser forming and engraving. The system utilises a single mover and tile to control the workpiece's position, speed, and acceleration. This novel approach demonstrates the feasibility of hybrid manufacturing by integrating laser forming and laser engraving. Initial testing has achieved an open-loop precision of $\pm$ 2° and a resolution of 124 dots per inch, indicating a potential for further optimisation and hybrid manufacturing. [9] The system is structured as a three-tier framework comprising a cloud layer, a control unit, and reconfigurable hardware. Each tier contributes to the overall system flexibility: the cloud layer interprets customer requirements and translates them into processing parameters; the control unit manages execution based on these parameters; and the reconfigurable hardware enables physical adaptability, allowing the system to accommodate varying product specifications and production demands. Such a system has the potential to solve manufacturing challenges regarding customisability and waste challenges in the industry. This leads to the initial objectives and research statement for the master's thesis.

The objective of this master's thesis is to analyse the possibilities of this proposed flexible manufacturing system for sheet metal manufacturing. Through the outlined research objectives listed below, this thesis aims to answer the proposed initial research statement:

"How can the proposed laser process system be integrated within the industry to address challenges for both traditional and existing laser-based processing processes?"

Initial objectives:

- *Conduct a literature study on processes within the sheet metal industry.*

  Investigating the sheet metal industry, identifying existing gaps, and evaluating the impact of laser technology on the industry.

- *Perform a literature study on process systems in laser processing.*

  Analyse existing process designs in laser technology for sheet metal manufacturing and evaluate how the experimental system integrates within the industry.

- *Define flexibility for the experimental system regarding product variety and volume.*

  Assessing the areas where the experimental laser processing system may require further refinement to ensure its industry relevance and competitiveness.

- *Design of fixture for magnetic levitation system for quality and assessment of limitations for fixture design.*

  Develop an approach to evaluate the constraints of the proposed system and determine its industry relevance based on the earlier objectives.

2. Problem Analysis

The problem analysis is based on a two-stage literature study. The first stage studies the current sheet metal manufacturing techniques, emphasising the focus of the industry on cost-effective, high-throughput production lines, often at the expense of flexibility. The second stage examines laser processing systems and compares them to the experimental system introduced in Chapter 1, aiming to identify industry demands and gaps to assess whether the proposed system can address these needs. A challenge identified in the sector is the limited flexibility of current systems, which hinders process integration. The analysis explores the advantages and trade-offs of incorporating flexibility into laser systems and assesses the experimental laser system against five flexibility measures alongside existing laser process systems.

2.1 Literature Study

This section contains a two-stage literature study on the processes performed in the sheet metal industry and the method used, diving into the advantages and disadvantages of different techniques and the performance metrics. The literature study explores the potential of a manufacturing system relying solely on laser techniques.

2.1.1 Methodology

An extensive literature study is conducted on thin sheet metal manufacturing techniques, including cutting, forming, welding, and finishing. The study draws upon resources from the Aalborg University Library and Google Scholar, combined with AI-powered literature search engines to ensure a comprehensive exploration of the topic. The study is conducted in two stages: initially, it examines the broader field of sheet metal manufacturing techniques, followed by a deeper focus on laser processing systems used in sheet metal fabrication. In the first stage, searches are performed using the prefixes “Sheet metal” or “Performance metrics in” and the suffixes “tools/machinery” or “processes,” combined with the following keywords:

- Cutting
- Forming
- Welding
- Finishing
- Fabrication
- Laser*
- Cost

In the second stage, the search is narrowed to include literature specifically containing the keyword "laser," focusing on laser processing technologies for sheet metal fabrication. Comparing common laser processing systems with the novel planar motor-based approach to assess their usage within the industry.

2.1.2 Literature Study on Sheet Metal Manufacturing Techniques

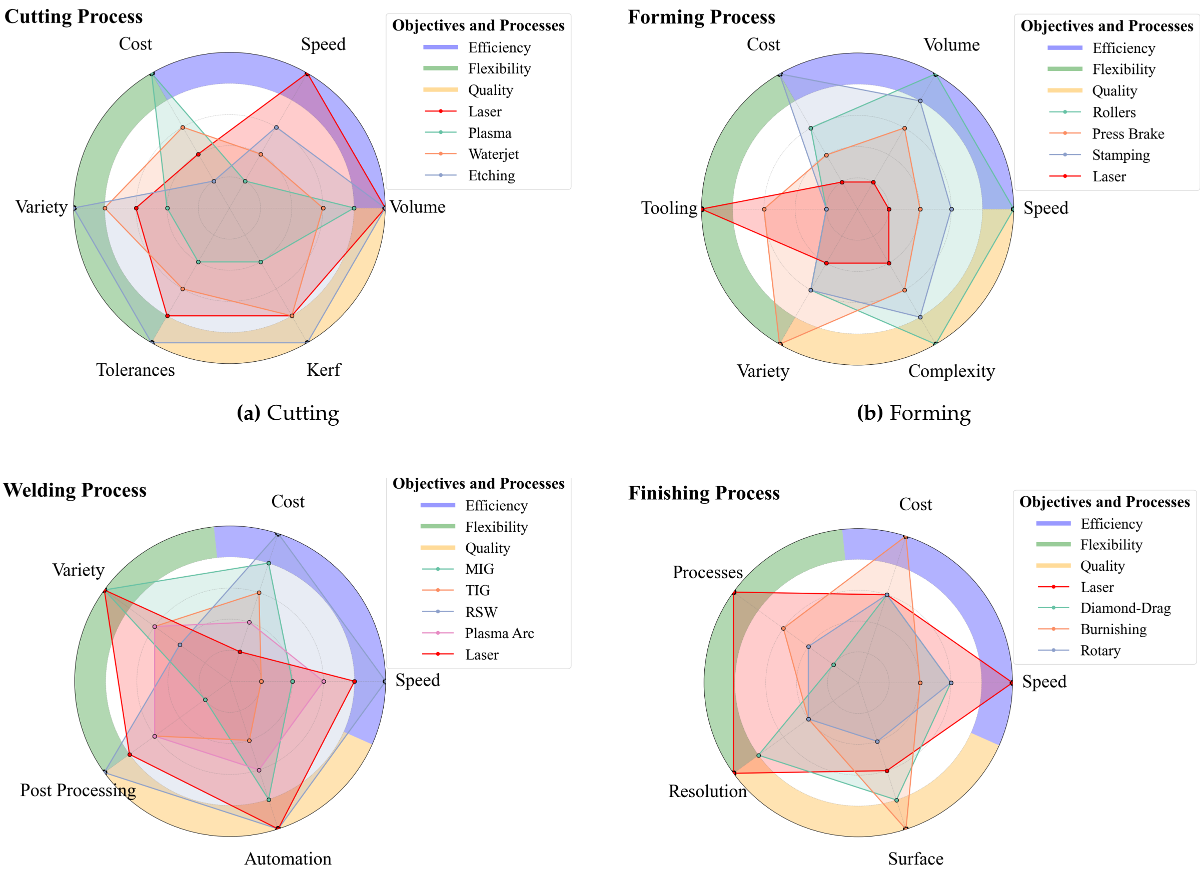
The first literature study hypothesises that current production systems in the sheet metal industry primarily prioritise efficiency and quality, as they are predominantly designed for high-volume, low-variety manufacturing. The results of this study are presented in Table 2.1, which provides an overview of the key industries that rely on sheet metal processing. The table compares various methods across four primary manufacturing techniques, cutting, forming, welding, and finishing, and highlights the relative advantages of each method within specific industrial areas.

Literature Study: Sheet Metal Industry Technique Comparison

Technique	Methods	Industry	Volume	Speed	Precision	Consistency	Cost	Sources
Cutting	Waterjet	Aircraft, Automotive, Defence, Ship Building	•••	••	•••	-	•••	[10, 11, 48]
	Plasma	Aircraft, Small metal shops	••••	•	••	-	••••	[10, 11, 48]
	Etching	Electronics, Medical	•••••	•••	•••••	-	•	[49, 50]
	Laser	Aircraft, Automotive, Electronics, Defence	•••••	•••••	••••	-	••	[10, 11, 12, 48, 51]
Forming	Roll	Construction, Automotive, Solar Energy	•••••	•••••	-	••••	•••	[5, 10]
	Press Brake	Automotive, Construction	•••	••	-	•••	••	[5, 10, 12, 51]
	Stamping	Automotive, Packaging/-Containers	••••	•••	-	•••••	•••••	[5, 10, 12, 51]
	Laser	Electronics	•	•	-	••	•	[4, 13]
Welding	Metal Inert Gas	Automotive, Metal Construction	••••	••••	-	••	••••	[14, 52, 53]
	Tungsten Inert Gas	Automotive, Aerospace, Fabrication Industry (Stainless Steel)	••	••	-	••••	•••	[14, 52, 53, 54]
	Resistance Spot Welding	Automotive, Production of Home Appliances	•••••	•••••	-	•••••	•••••	[14, 10, 52]
	Plasma Arc	Automotive, Aerospace, Medical	•••	•••	-	•••	••	[14, 10, 52, 54]
	Laser	Automotive, Medical, Aerospace and Electrical Industries	•••••	•••••	•••••	•••••	•	[10, 14, 15]
Finishing	Rotary	Automotive, Jewellery	••••	••	••	••	•••	[16, 55]
	Diamond-Drag	Jewellery, Automotive	••	•••	••••	••••	•••	[16, 55]
	Burnishing	Jewellery	••	•••	••	•••••	•••••	[16, 55]
	Laser	Automotive, Pharmaceuticals, Electronics, Jewellery	•••••	•••••	•••••	•••	•••	[16, 55]

Table 2.1: Overview of thin sheet metal manufacturing techniques, comparing different methods. The table highlights their industrial applications, relative performance across key categories, and the literature sources referenced. The scores in columns 4 to 8 represent comparative assessments within each category. For further details and data, see Appendix A.

The literature study reveals that laser processing is widely applied in three of the four main manufacturing techniques, cutting, welding, and finishing, while remaining underutilised in forming. It further underscores the advantages of laser technology over conventional methods, particularly in terms of speed and scalability in high-volume applications. To support the hypothesis, the findings from Table 2.1 are visualised using radar plots, which classify the different production methods according to the core process design objectives: efficiency, flexibility, and quality. These visual comparisons are presented in Figure 2.1. To better understand the variation in performance across techniques, a more detailed examination of the underlying metrics associated with each process is required. [17, 18].



(a) Cutting **(b)** Forming **(c)** Welding **(d)** Finishing

Figure 2.1: Radar plots comparing laser processing (highlighted in red) to other methods across cutting, forming, welding, and finishing. The plots illustrate the relative performance of each technique based on core process design objectives: Efficiency, Flexibility, and Quality.

Elaboration on the comparison parameters used in Figure 2.1 can be seen in Table 2.2. Some comparison parameters are repeated across the manufacturing techniques as they are common; these include cost, speed, and volume. Parameters not repeated only share that they fall under the same process design objective, but are not measured in the same way. In general, the metrics are standard comparison parameters in each discipline of the sheet metal industry and are self-explanatory. However, few require further explanation, these metrics are marked with (*).

Cutting Process
Cost: *Price for system*
Speed: *Cutting speed*
Volume: *Products per batch*
Kerf: *Quality of the cut surface*
Tolerance: *Precision achievable*
Variety: *Thickness and materials possible*

Forming Process
Cost: *Price for system*
Speed: *Production speed*
Volume: *Throughput (1–100, 101–1000..)*
Complexity: *Measure of how complex a part that can be produced.**
Tooling: *Generic or complex tools needed.**
Variety: *Thickness possible*

Welding Process
Cost: *Price for system and tools*
Speed: *Weld speed*
Automation: *Possibility for automation*
Post Processing: *Work needed to treat or clean weld*
Variety: *Thickness, materials and geometries possible*

Finishing Process
Cost: *Price of system*
Speed: *Scan speed/feed rate*
Surface: *Quality after processing*
Resolution: *Smallest detail achievable*
Variety: *Possible finishing processes*

Table 2.2: Explanation of performance metrics used in the radar plots (Figure 2.1) for cutting, forming, welding, and finishing.

Complexity refers to the level of geometric variation a system can accommodate during production. [19] A low complexity score indicates a constrained setup suitable for simple parts, whereas high complexity reflects the capability to produce a wide range of geometries. Tooling refers to the degree of standardisation or customisation required for the tools used in production. It directly influences the lead time from finalised design to initial production, as well as the changeover time between different product variants. Meaning that higher standardisation is preferred.

The performance comparison between traditional methods and laser technology, shown in Figure 2.1, highlights lasers' superiority in cutting, welding, and finishing. With scores of 23 in cutting, 19 in welding, and 21 in finishing. This is due to the inherent capabilities of speed, precision, and automation of lasers as of Table 2.1. However, lasers remain less effective in forming due to cost inefficiencies and volume limitations, compared to traditional methods, where they excel in large-scale operations as seen in 2.1, supporting the stated hypothesis. Nonetheless, the versatility of lasers suggests that a production system relying solely on laser tooling could provide a complete solution for rapid prototyping or low to medium volume production, offering performance advantages over traditional systems in terms of flexibility.

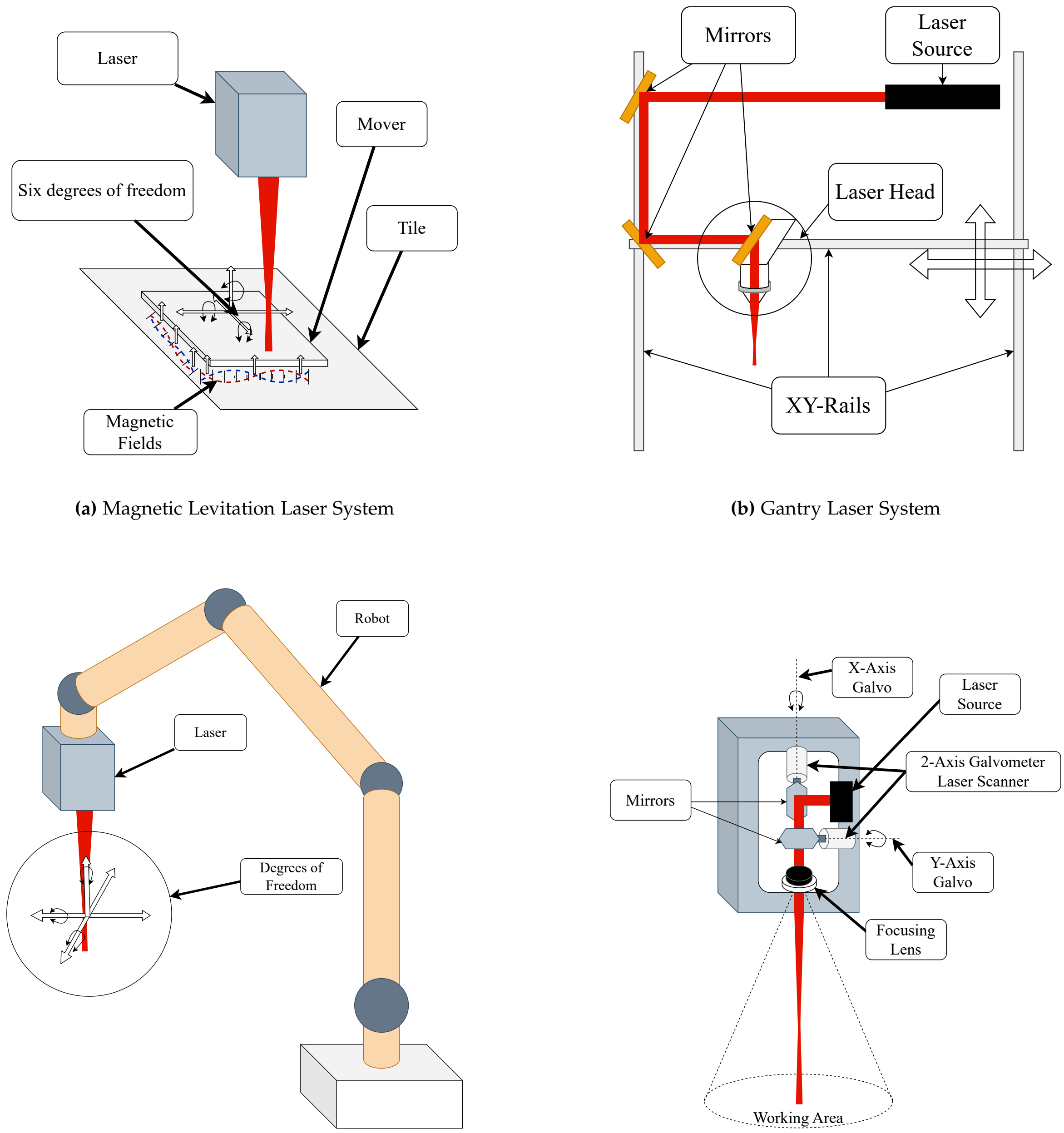
2.1.3 Literature Study on Laser Processing Systems

The second literature study hypothesises that workpiece manipulation enhances flexibility, and is a viable option for job shop, low volume productions and rapid prototyping. The first literature study on sheet metal manufacturing techniques identifies laser processing as a suitable method for all four investigated processes, supporting their integration into a single production system. Given that laser forming differs significantly from conventional forming in production volume and speed, overall flexibility becomes the primary focus. To further explore this potential, the second stage study examines laser manufacturing systems within the sheet metal industry, investigating their processes, capabilities, process types, and design objectives. By identifying gaps in integrating multiple laser processes into a single system for low to medium-volume production and assessing the benefits and downsides of such an approach. Furthermore, it seeks to understand the challenges of adopting laser technology for forming applications despite its demonstrated ability to shape sheet metal efficiently. [4, 51]

The comparative analysis is conducted on three commonly used laser processing systems: robotic, gantry-based, galvo, and the proposed magnetic levitating laser processing system. The four different systems are illustrated in Figure 2.2. This comparison not only evaluates the suitability of each system for specific manufacturing processes, but also classifies the best-suited process types: job shop, batch, repetitive, continuous, and project-based manufacturing [17] to asses whether it is a suited system for low to medium volume production.

- **Job Shop**: Highly flexible process designed for custom, low-volume production.
- **Batch**: A low to mid-volume production approach where parts are processed in groups.
- **Repetitive**: A standardised, mid to high-volume production with lower variation.
- **Continuous**: A fully automated, high-volume process designed for efficiency.
- **Project**: A unique and large-scale complex process with a defined start and end.

Furthermore, relevant specifications are incorporated into the comparison to assess the process systems' relevance for performing the desired task, as listed in Table 2.3, while providing data-driven reasoning for selecting one process system over another. As outlined in the conference article Chapter 3, experimental investigations have been conducted, yielding data related to process characteristics, classifications of process types, and corresponding process design objectives.



(a) Magnetic Levitation Laser System

(b) Gantry Laser System

(c) Robot Laser System

(d) Galvo Laser System

Figure 2.2: Overview of the four laser system configurations considered in the project: Galvo, Gantry, Robot, and Magnetic Levitation.

Comparison between Laser Process Systems

System	Robot	Gantry	Galvo	Magnetic Levitation
Achievable Processes	Welding [20] Cutting [4, 20, 21] Forming [4]	Welding [22, 56] Cutting [21]	Cleaning Marking [57, 58] Engraving [57] Cutting [23, 58] Welding [57]	Forming Ch[3] Engraving Ch[3]
DOF	6 [59]	2 [56, 60]	2 [57, 58]	6(3)* [61]
Speed	0.25 m/s	1.5–2 m/s [56, 60]	+7 m/s [62]	3 m/s [61]
Accuracy	0.45(0.05)** mm [24]	0.05 mm [60]	0.001 mm	0.001 mm [61]
Workspace	Reach 2.8 to 3.7 m [59]	4 m × 2 m [60]	0.2 m × 0.2 m [62]	3.6 m^2 per IPC [61]
Workpiece Thickness	Varying	Thick	Thin***	Thin Ch[3]
Process Type	Repetitive [20] Batch [25] Project [20]	Job Shop Repetitive [56]	Continuous [58] Batch [57]	Job Shop Ch[3] Batch Ch[3] Rapid Prototyping Ch[3]
Process Design Objective	Speed [20] Quality [20]	Speed Quality Flexibility [56]	Quality [58] Speed [57] Dependability [58]	Speed Ch[3] Quality Ch[3] Flexibility Ch[3]
Manipulation	Laser or part	Laser (or part)	Laser	Part
Transport of Part	✓****	×	×	✓
Workpiece Fixture	Large shared fixture	Large shared fixture	Small shared fixture	Multiple individual fixtures

Table 2.3: *Limited in vertical movement (5 mm) and rotation around x and y (5°). **Higher accuracy can be achieved with external CNC control. ***Only relevant for cutting. **** Within the workspace of the robot.

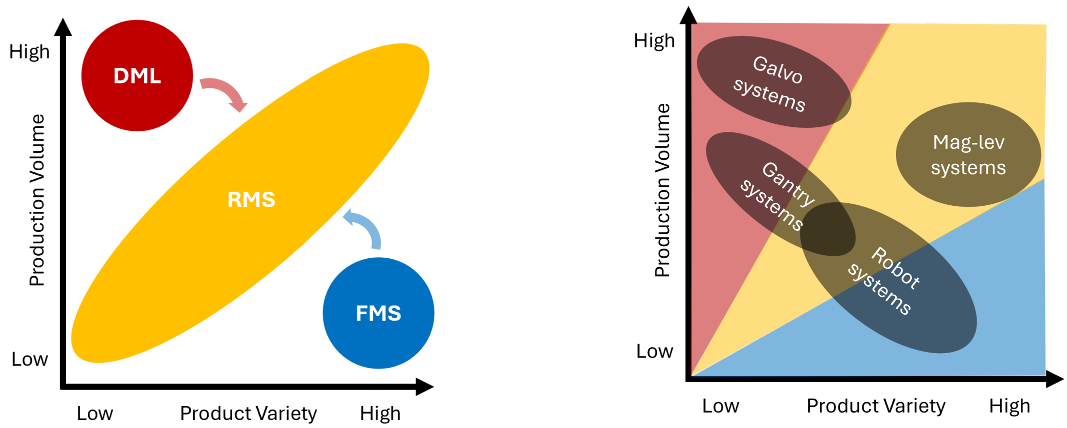
Table 2.3 shows that robots are the most versatile systems, capable of performing three different processes across three process types. Additionally, robots, galvo scanners, and gantry systems are well-researched, particularly in terms of speed and quality for mass production. In contrast, the magnetic levitation table represents a novel approach. While process characteristics, classifications, and design objectives are primarily derived from the conference article in Chapter 3, the technical specifications stem directly from the investigated system, which is based on planar motor technology, indicating that the system is not fully researched. As shown in Table 2.3, laser forming is predominantly supported by flexible systems, as the iterative nature of the process makes it best suited for low-volume production environments. It is found that flexibility is enhanced by enabling workpiece movement, allowing the system to transport parts and accommodate various products using individual fixtures. This suggests that the magnetic levitation table system has the potential to integrate all processes into a unified system, offering enhanced flexibility through workpiece manipulation.

2.1.4 Summary of Literature Study

The first stage of the literature review explores the role of laser processing in sheet metal processes such as cutting, welding, and finishing, highlighting their superior speed and precision. However, lasers are limited in forming applications due to the cost-volume trade-off compared to traditional manufacturing systems. The second stage emphasises that while lasers excel in high-volume production, their flexibility is underutilised in low- to medium-volume settings. The study also identifies a gap in the industry. Current systems excel in dedicated processes like welding (robots), finishing (galvo scanners), and cutting (gantry systems). There is a need for a laser-based solution that incorporates all processes into one. The potential integration of multiple laser processes into a single system, specifically a magnetic levitating table, could enhance flexibility by moving the workpiece rather than the tool head, offering significant benefits for job shops, prototype production, and low-volume manufacturing.

2.2 Taking Advantage of Flexibility

As outlined in both stages of the literature study, current laser cutting, welding, and finishing rely on dedicated manufacturing lines (DML) optimised for mass production or specialised in one process, achieving a low cost per produced unit but minimal flexibility. [26] As shown in Table 2.3, laser forming is primarily supported by highly flexible manufacturing systems (FMS) tailored for low- to medium-volume batch production. The associated process types indicate a focus on low-volume output, which in turn reflects a high degree of product variety. A balance between these two scenarios might be relevant for the sheet metal industry, as there is an increasing demand for customised parts with larger order sizes. The reconfigurable manufacturing system (RMS) bridges this gap, offering greater market adaptability than flexible manufacturing systems and lower lead times compared to dedicated systems. [26, 27, 28] While it may not match the production volume of dedicated systems, it combines the advantages of both, achieving the right balance of flexibility for laser sheet metal manufacturing, illustrated in Figure 2.3a. Plotting the laser systems from Table 2.3 using their applicable process type according to [17] yield the graph shown in Figure 2.3b. This further underscores that a system that combines dedicated and flexible systems is missing in the industry.



(a) Production volume vs variety flexibility, adapted from [29].

(b) Comparison of the laser systems from Table 2.3 based on defined process type.

Figure 2.3: Visual definition of an RMS and representation of the discussed manufacturing systems.

From an industrial perspective, incorporating flexibility into production systems can provide a competitive advantage. As flexibility can be defined as "the ability to neutralise the effect of demand uncertainty", and is a fundamental aspect of modern process system design. [26, 30] The aspect of flexibility can enhance utilisation rates, reduce work-in-progress, leading to lower lead times, while improving responsiveness to market shifts as process and product changes align. [26, 27] Flexibility also facilitates an increased product variety, new products and processes that can be integrated more easily into the production systems. [31] This aligns with the demands of sectors that rely on sheet metal products and properties, as discussed in Chapter 1. Consequently, this thesis further examines the balance of flexibility, its definitions, trade-offs, and the challenges associated with incorporating flexibility into laser sheet metal manufacturing.

The generalised concept of flexibility considered in the literature study should be decomposed into finer subdimensions to explore its critical aspects. [32] These dimensions can then quantify the trade-off between the opposing process design objectives, efficiency and quality. When adjusting the quantifiable flexibility dimensions, the right level of flexibility can be achieved. [27] Quantifiable flexibility regarding general manufacturing systems is a rigorously studied field, and consensus regarding the relevant objectives and measurements is achieved for the relevant flexibilities listed below. [30]

- **Volume**: Capability to operate at different levels of output, with limited financial restraints.
- **Product**: Ability to create or substitute new products quickly.

- **Mix**: Capability to respond quickly and economically to different product mix.
- **Expansion**: Ease with which the system scales and capacity can be added.
- **Routing**: Capability to use alternative sequences or routes to make a product.

Currently, laser forming remains under-researched, which limits its economic feasibility for widespread industrial application. Introducing the mentioned flexibility measures as variables, the right level of flexibility can be achieved by transforming the flexible laser forming system into a reconfigurable manufacturing system. Adjusting these flexibility dimensions can impact each other, but in common they all have a financial impact due to the high initial investment in flexible systems. [26] Trade-offs and synergies between the above-mentioned flexibility dimensions are therefore explored further. Increasing product flexibility can reduce volume flexibility due to added complexity and changeover times. [30] Similarly, increasing mix flexibility may constrain volume flexibility if scheduling and resource allocation are not optimised accordingly. However, by enabling rapid adaptation to market changes, the system can reduce the need for large inventory buffers and minimise the risk of lost sales by supporting just-in-time manufacturing. [31] Routing flexibility enhances both mix and volume flexibility by reducing bottlenecks, however excessive routing options may lower volume flexibility by complicating workflows. Meanwhile, expansion flexibility supports volume flexibility but can impose new routing and scheduling constraints if not managed properly. Leading to an unsustainable scalability of the system. [30, 31] Adjusting the flexibility dimensions is done on different levels of the manufacturing system, ranging from component level to operations management. [28] Volume and product flexibility are adjusted by the means of tools, fixtures, and machinery at the lowest level of a manufacturing system. [28] Meanwhile, mix, expansion and routing flexibility is mainly assessed through digital components such as Cyber Physical Systems and IoT. [33]

2.2.1 Assessment of Experimental System and Scoping Problem

The experimental system, as introduced earlier, must be assessed in relation to the previously defined flexibility dimensions. [26, 30] To facilitate this assessment, the system specifications and prior experimental results are taken into account 3. The assessment framework for the systems is illustrated in Figure 2.4. The framework compares all investigated laser-based processing systems across the five identified flexibility dimensions. The purpose is to evaluate which system demonstrates a potential for improving production flexibility and should therefore be prioritised for further investigation in regards to underutilised flexibility dimensions.

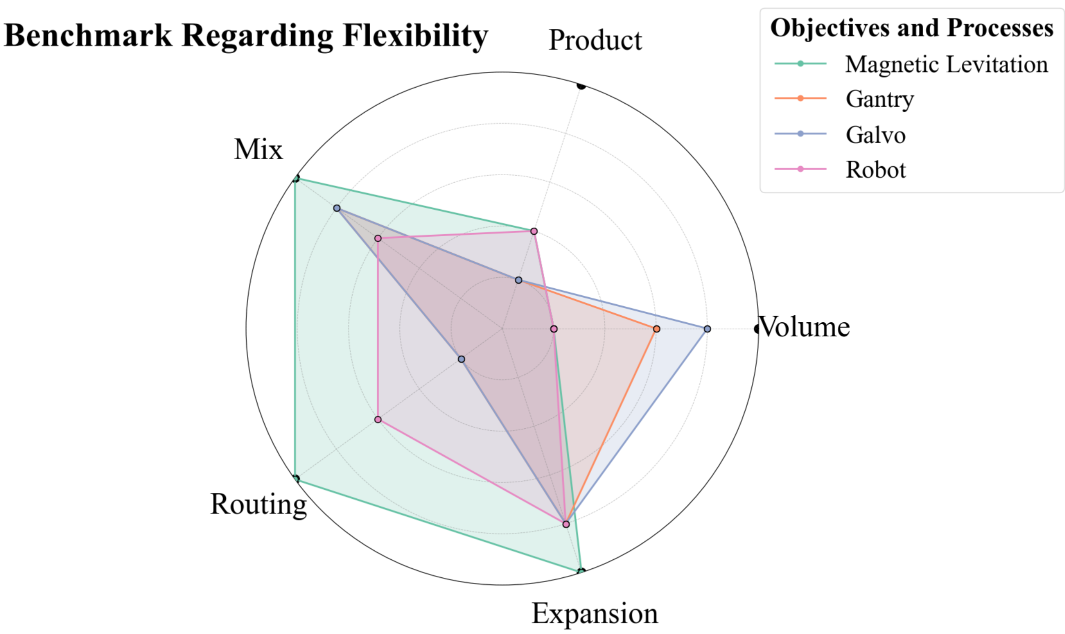


Figure 2.4: Assessment of the proposed magnetic levitation system against the five flexibility dimensions and compared to existing laser-based production systems.

Figure 2.4 highlights the need for system modifications to enhance industrial relevance, as the literature points to a growing industry emphasis on volume and product flexibility, as the first literature study suggested. A further description of the evaluation of each flexibility dimension is done in Table 2.4. To address this, targeted redesigns are needed within the three-tier framework of the experimental magnetic levitation laser process system in either the cloud, the processing control unit, or the hardware. [28] Identifying the appropriate level to modify is essential, particularly with respect to volume and product flexibility, as these needs vary depending on the capabilities of the system. In the case of the magnetic levitation system, these flexibilities are influenced at the lowest structural level, tools (hardware), requiring a fixation or adaptive method to support greater flexibility in both volume and product variation. [28]

System	Mix		Routing		Expansion		Product		Volume	
Mag-lev	**5:**	Highly flexible, processes individual fixtures randomly	**5:**	Enables independent fixture movement	**5:**	Modular tiles, fixtures, and laser tools allow full process scalability	**2:**	Limited by fixture design constraints	**1:**	Not researched for volume flexibility
Robot	**3:**	Some flexibility, but best for repetitive tasks	**3:**	Limited by reach and transport capabilities	**4:**	Can scale by adding more robots	**2:**	Constrained by fixture design	**2:**	Effective for repetitive tasks but costly for low-volume production
Galvo	**5:**	Highly flexible processing	**1:**	Cannot move the workpiece	**4:**	Can scale by adding more galvo systems	**1:**	Lacks workpiece manipulation capability	**4:**	Low to zero scaling costs
Gantry	**4:**	Good flexibility, suitable for job shop processes	**1:**	No movement, functions as a dedicated system	**4:**	Can scale by adding more gantry systems	**1:**	Cannot manipulate workpieces	**3:**	Primarily used in job shop environments

Table 2.4: Comparison of manufacturing technologies based on five flexibility dimensions: Mix, Routing, Expansion, Product, and Volume. The numerical rankings reflect the relative performance in each category and correspond to the radar chart shown in Figure 2.4.

2.2.2 Summery

Quantifying the flexibility dimensions is often done financially. A flexible system strategically balances these costs to maximise efficiency and responsiveness. Volume flexibility determines cost efficiency at different production levels, measured through cost per unit, with higher flexibility reducing per-unit costs. Product flexibility incurs changeover and customisation costs, affecting downtime and R&D expenses. Mix flexibility minimises lost sales and inventory holding costs by adapting to demand shifts. [31] Routing flexibility optimises system utilisation and reduces idle time costs, improving operational efficiency. [28] Lastly, expansion flexibility is evaluated by scalability costs. [31] Increasing flexibility involves the development of fixation or cutting techniques to enhance both volume and product flexibility. Given that the system already excels in other areas based on Table 2.4 and Chapter 1, the focus will be on addressing these two flexibility types. In this context, the developed experimental laser process system, introduced in Chapter 1, offers the ability to adjust flexibility concerning the mix, routing, and expansion of the system. This is made possible through the integration of digital components such as cyber-physical systems and Internet of Things. [33].

3. Conference Article

From the problem analysis, it became evident that further research was necessary to investigate the feasibility and industrial potential of the magnetic levitation table. To support this, a dedicated conference article was prepared, presenting supplementary experiments and analyses conducted alongside the master's thesis. Selected findings from this article were incorporated into the problem analysis to help position the proposed system in relation to existing industrial laser technologies. The conference article is currently under review pending publication.

The article investigates the application of magnetic levitation laser-based processing for the production of customised sheet metal components, such as name tags. It benchmarks the experimental system against established robotic and galvo-based laser systems, with a focus on evaluating performance in terms of flexibility, processing speed, and geometric accuracy in forming and engraving operations.

The results presented in the article indicate that magnetic levitation systems offer a compelling alternative for industries requiring high adaptability and customisation. While the system demonstrates comparable performance to conventional solutions, further research is necessary to address remaining challenges in cost-efficiency, scalability, and real-world implementation for more complex production scenarios. These challenges inform and motivate the subsequent chapters of this thesis.

In addition to the article (included below), detailed descriptions of the experiments and results can be found in Appendix B.2.

Magnetic Levitation for Laser Processing

Mads H Andersen[1], **Mads A Frøhlich**[1] **and Morten Kristiansen** [1,2]

[1]Department of Materials and Production, Aalborg University, Aalborg, Denmark

E-mail: [2]morten@mp.aau.dk

Abstract. The sheet metal industry prioritises speed and efficiency, often at the cost of flexibility in process design. Laser processing, while versatile, is predominantly optimised for speed, limiting its adaptability in manufacturing. This article addresses the need for more flexible systems, evaluating a magnetically levitating table as a novel solution for seamless transitions between processing stages, with the added potential to transport multiple parts simultaneously using individual moving fixtures. Testing compares three process systems—robot, galvo, and an experimental magnetic levitation system—for forming and engraving applications. The results support the hypothesis that the magnetic levitation system offers a balanced solution in process design objectives, speed, flexibility, and accuracy. With demonstrated capabilities in forming and engraving, it shows promise at higher production scales as an all-in-one platform. By processing multiple parts simultaneously using individual movers, it is well-suited for job shop operations, rapid prototyping, and low-to-medium volume batch production of small components. Combining the speed of galvo systems and the flexibility of robotics, the magnetic levitation approach combines process design objectives and reconfigurable manufacturing principles.

1 Introduction

The sheet metal industry is essential to modern manufacturing, as it is used in sectors such as construction, automotive, aerospace, and consumer electronics, where the most common materials are steel and aluminium. [1]. In 2023 the global sheet metal market size, only including steel and aluminium, was valued at USD 188.31 billion [1]. When including other metals, the market size is valued from $\approx$ USD 350-430 billion [1].
The advancement of sheet metal processing is increasingly driven by laser technology, a key enabler of manufacturing efficiency and precision. Due to its inherent characteristics, laser processing is well-suited to be employed in numerous processes, including joining, fabrication (e.g., additive manufacturing), machining, forming, and finishing [2, 3]. While laser technology is predominantly used in cutting, welding, and finishing, recent research has begun exploring its potential for laser forming of sheet metal, making it a versatile tool [4]. However, manipulation for laser processing presents challenges in maintaining both speed and accuracy, particularly when dealing with complex geometries. These difficulties become more pronounced when processing shapes beyond flat surfaces, where precise and accurate control over positioning and movement is crucial to achieving the desired geometries.

Within the sheet metal industry, various production strategies are employed depending on the application. Robots are commonly used for cutting, welding, and, more recently, forming [4, 5, 6]. Gantry systems are utilised for processes such as welding and cutting large components [7, 8], while galvo laser systems, excluding wobbling heads, enable high-speed processing operations for complex patterns in finishing, welding and ablation [9]. A common trend across all production strategies is the focus on process design objectives, primarily speed, quality, and cost—while more advanced systems, including robotic setups, also emphasise dependability [10, 11].

1.1 Need for a Flexible System

Lasers are a highly versatile tool, making them an ideal choice for multiple processes, a single technology capable of addressing various manufacturing needs [2]. However, one crucial process design objective is often overlooked, flexibility. As highlighted by [10] and [11], flexible systems can seamlessly transition between states, respond to system failures, and prevent complete shutdowns, enhancing overall manufacturing resilience [10].

Systems emphasising flexibility are referred to as flexible manufacturing systems, characterised by supervisory computer control, automated processing equipment, and automatic material handling. [10] Using reconfigurable control systems and hardware allows these systems to manufacture various products in a confined product family. The latter of the aforementioned characteristics are difficult to achieve using the presented production strategies as they lack the ability to manipulate the workpiece and only focus on the manipulation of the laser beam exiting the tool head or tool head. Workpiece manipulation would lead to flexibility in a production system. A well-suited candidate for this is a magnetic levitating table based on the "Sawyer motor" introduced by Bruce Sawyer. [12]

1.2 Comparison of Process systems

A comparison of process systems is performed to form a basis for informative decisions on which system to choose. In addition to which processes the system is well suited for, this comparison classifies the system into one or more of the following process types: job shop, batch, repetitive, continuous, and project [10] to asses whether it is a suited system for low to medium volume production.

- **Job Shop**: A highly flexible process type designed for custom, low-volume production.
- **Batch**: A mid-volume production approach where parts are processed in groups.
- **Repetitive**: A standardised, higher-volume production process with lower variation.
- **Continuous**: A fully automated, high-volume process designed for efficiency.
- **Project**: A unique, large-scale, and complex process with a defined start and end.

Furthermore, relevant specifications are incorporated into the comparison to assess the strategies' relevance for performing the desired task, as listed in Table 1, while providing data-driven reasoning for selecting one process system over another.

Comparison between Laser Process Systems

System	Robot	Gantry	Galvo	Mag-Lev
Achievable Processes	Welding [13] Cutting [4, 6, 13] Forming [4]	Welding [7, 8] Cutting [6]	Cleaning Marking [14, 15] Engraving [14] Cutting [16, 15] Welding [14]	
DOF	6 [17]	2 [18, 7]	2 [14, 15]	6(3)* [19]
Speed	0.25 m/s	1.5-2 m/s [18, 7]	+7 m/s [20]	3 m/s [19]
Accuracy	0.45(0.05)** mm [21]	0.05 mm [18]	0.001 mm	0.001 mm [19]
Workspace	Reach 2.8 to 3.7 m [17]	4 m x 2 m [18]	0.2 m x 0.2 m [20]	3.6 m^2 per IPC [19]
Workpiece Thickness	Varying	Thick	Thin***	-
Process Type	Repetitive [13] Batch [22] Project [13]	Job Shop Repetitive [7]	Continuous [15] Batch [14]	
Process Design Objective	Speed [13] Quality [13]	Speed Quality Flexibility [7]	Quality [15] Speed [14] Dependability [15]	
Manipulation	Laser or part	Laser (or part)	Laser	Part
Transport of Part	✓****	✗	✗	✓
Workpiece Fixture	Large shared fixture	Large shared fixture	Small shared fixture	Multiple individual fixtures

Table 1: *Limited in vertical movement (5 mm) and rotation around x and y (5°). **Higher accuracy can be achieved with external CNC control. ***Only relevant for cutting. **** Within the workspace of the robot

Table 1 highlights that robots, galvo scanners, and gantry systems are well-researched regarding their applications and inherent capabilities, with a common focus on speed and quality for mass production and high-volume production. In contrast, the magnetic levitation table is a novel approach with no established data on applicable processes or design objectives, therefore data is not provided in the table.

An experimental system is thus needed to evaluate its capabilities, classify its suitability for various laser processes, and identify potential advantages over existing systems.
The parameters of the different processing systems presented in Table 1 support the hypothesis that the magnetic levitation system offers a promising solution for low-to-medium volume production and rapid prototyping, positioning itself as a balanced option between speed, flexibility, and accuracy.

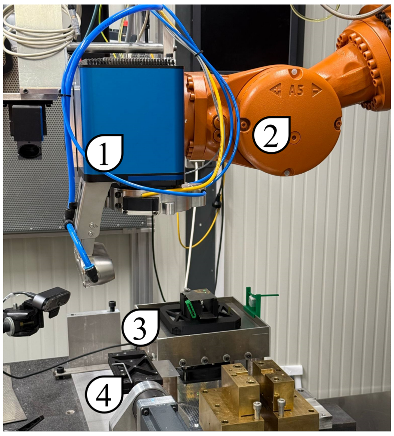
2 Methods

An experimental processing system based on a magnetic levitation table was developed to evaluate its performance, advantages, and limitations relative to existing technologies. This evaluation was carried out through an initial feasibility study, followed by an early-stage benchmarking study. To address gaps in comparative analysis, experiments with the prototype alongside robotic and galvanometer-based laser systems provide a quantitative evaluation of industrial relevance and process capabilities. The experimental setup, shown in Figure 1a, integrates these components:

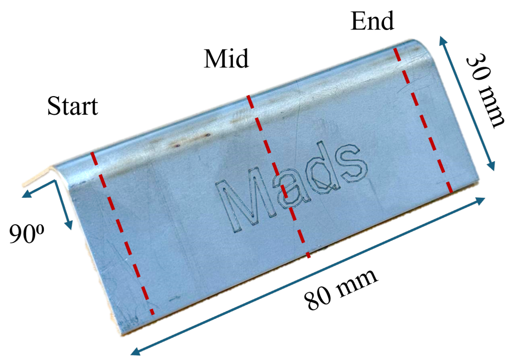
Laser System and Processing Platform Specifications

Parameter	**Description**	**Specifications**		
Model	*Laser source model*	IP6 YLS-3000-SM		
Wavelength [nm]	*Laser wavelength*	1076		
Power [kW]	*Maximum power*	3		
Focal length [mm]	*Focal length*	490±25		
PLC	*Control system*	Beckhoff		
Processing System		**Mag-Lev XPlanar**	**Galvo Arges**	**Robot KUKA**
Movers / Tiles	*Platform movers/tiles*	1 / 1	–	–
Speed [mm/s]	*Process speed*	F: 45 / E: 100	F: 50 / E: 1000	F: 100 / E: 200
Power [W]	*Available power*	F: 240 / E: 60	F: 260 / E: 55	F: 260 / E: 90
Spot size [mm]	*Beam spot diameter*	F: 0.468 / E: 0.275	F: 0.270 / E: 0.131	F: 0.270 / E: 0.131

Table 2: Individual laser-source specifications and Beckhoff PLC control system. Forming (F) and engraving (E) parameters for XPlanar, Galvo and KUKA system.



(a) Experimental setup illustrating **1**: Arges galvo System. **2**: KUKA KR120 R2500 Quantic HA robot. **3**: Beckhoff XPlanar system consisting of a tile and mover with 3D printed fixture. **4**: Fixture (Galvo, Robot).



(b) Name Tag with task of engraving customisable text (4 characters) and forming a 90-degree bend. Measuring points are illustrated with red dashed lines at 5 mm, 40 mm and 75 mm.

Figure 1: Picture of experimental setup and name tag

A name tag is selected as the test part for evaluating the processing systems, as shown in Figure 1b. This choice is based on the precision and repeatability required for the forming process, which demands consistency, efficiency, and reliability. [4] For engraving, the focus is on customisation, necessitating high positioning accuracy and a flexible yet rapid process. Given the distinct requirements of these processes, the overall system must also remain flexible yet cost-effective for it to function in an industrial setting. Laser cutting is excluded due to the need for a dedicated waste collection bin, while the feasibility of forming and engraving is assessed. Efforts are made to standardise experiments comparing processing systems; however, methodological differences remain. The magnetic levitation system uses pulse width modulation-based power control and G-code-based pathing, whereas the process scanner and KUKA robot utilise direct wattage control with extensible markup language-based programming for motion tasks. Each system is individually calibrated for optimal spot size and motion, resulting in differences in the number of scan lines used during forming. All experiments were conducted using open-loop control. Initial tests determined the minimum engraving parameters needed for legible characters. In parallel, bending trials showed an average bend of 1.6° per scan; ≈56 scans were estimated to yield a 90° bend. This estimate was subsequently fine-tuned empirically until a consistent 90° bend was achieved. Ten replicate tests were performed using these settings. Potential sources of error are further discussed in the Sources of Error section.

2.1 Evaluation and Classification of Novel Laser Process System

The magnetic levitation table is classified according to process type and design objectives, addressing the gaps identified in Table 1. A methodology for classifying process systems is done by evaluating the processing system on the following criteria:

1. Cycle time
2. Throughput time
3. Processing speed
4. Consistency
5. Tolerances
6. Achievable processes

Criteria 1–3 relate to process design objective speed, criteria 2 and 5 to dependability, criteria 4–5 to quality, and criteria 1 and 6 to flexibility as a process design objective. [11] A system is classified under a specific process design objective if it outperforms competing systems in that category. Processing types are classified as follows: systems excelling in flexibility and dependability are flexible manufacturing systems, suited for job shop and low-batch production. [23, 11, 10] Systems with high speed and quality are dedicated manufacturing systems, ideal for medium-to-high-volume production. [24] Finally, systems demonstrating superior flexibility, quality, and speed are reconfigurable manufacturing systems, best for low-to-medium-volume production and rapid prototyping. [24, 25]

3 Results

Table 3 presents a comparative evaluation of the three laser processing systems based on key performance metrics, with brief descriptions of each parameter included for clarity.

Comparison of Laser Process Systems

Parameter	**Description**	**Robot KUKA**	**Galvo Arges**	**Mag-Lev XPlanar**
Cycle Time	*Per task*	E 1:40 / F 5:04	E 0:02 / F 4:04	E 0:05 / F 4:40
Total Time	*Full process*	6:44	4:06	4:45
Forming Angle	*Start / Mid / End*	94.4° / 94.4° / 94.4°	91.95° / 91.8° / 91.75°	91.25° / 91.6° / 91.5°
Tolerance	*Std. dev. (3 pos.)*	±1.27° / ±1.12° / ±1.17°	±1.24° / ±1.27° / ±1.44°	±1.57° / ±1.49° / ±1.35°
Engraving	*Surface finish*	Poor	Excellent	Good
Achievable Processes*	*Tested (supported) Valid***	2 (3) 1	2 (5) 2	2 (0) 2

Table 3: Comparison of laser processing systems. E = Engraving, F = Forming. *Refers to the theoretically supported processes from Table 1 **Valid indicates the number of achievable processes from Table 1 that were successfully executed with satisfactory results on each system.

3.1 Evaluation and Classification

Table 3 presents a comparative evaluation of three laser processing systems based on speed, quality, dependability, and flexibility. The robotic system is classified as a flexible/dedicated manufacturing system due to its high dependability and moderate flexibility, with known applications in welding indicating broader flexibility potential. While it achieves high dependability (forming angle: 94.4° at start, middle, and end; tolerance: ±1.27° / ±1.12° / ±1.17°), it exhibits a uniform bend profile across the part, indicating a high degree of process repeatability. However, it trends towards characteristics of dedicated machinery, with limited flexibility due to surface quality after engraving and a throughput time of 6:44. The galvo system, a dedicated setup, excels in engraving quality and speed (engraving cycle time: 0:02) but underperforms in forming, with angles of 91.95° / 91.8° / 91.75° (start/middle/end) and corresponding tolerances of ±1.24° / ±1.27° / ±1.44°, reflecting slight variation across the bend and reinforcing its role as a dedicated engraving system. The magnetic levitation system, evaluated and classified as reconfigurable, demonstrates balanced performance with high surface quality, consistent forming (angles: 91.25° / 91.6° / 91.5°; tolerances: ±1.57° / ±1.49° / ±1.35°), and competitive throughput (4:45). Although the forming profile shows slightly more variation than the robotic setup, the results remain consistent enough to support its suitability for mixed applications. Notably, both the galvo and magnetic levitation systems offer high potential in engraving applications, as their architectures minimise mass in motion, via mirrors in the galvo and workpiece manipulation in the magnetic levitation setup.

3.2 Sources of Error

During the comparison experiments, sources of variation were identified that may affect repeatability. The primary contributor to the variation in the resulting bend angle is attributed to inconsistencies in the metal plates themselves. These include differences in rolling direction, position within the sheet (e.g., side versus centre), and surface imperfections or residual stresses introduced during the cutting process. Additionally, the use of open-loop control, without real-time feedback, makes the process more sensitive to such material-related variations, as adjustments cannot be made during forming. Another reason for the differences lies in the fixation method: the robotic and galvo systems use rigid, motor-assisted fixtures ensuring consistent alignment, whereas the magnetic levitation system employs a custom 3D-printed fixture, introducing greater variability. Additionally, differences in power delivery and laser module count must be noted: the galvo and robotic systems utilise six laser modules, whereas the magnetic levitation system operates with a single module.

4 Conclusion

In conclusion, the results support the hypothesis that the magnetic levitation laser system offers a balanced solution in process design objectives, speed, flexibility, and accuracy. With demonstrated capabilities in forming and engraving, the system shows promise at higher production scales as an all-in-one platform. This could be done by processing multiple parts simultaneously using multiple movers. The system is well-suited for job shop operations, rapid prototyping, and low-to-medium volume batch production of small components.

5 Discussion

The results are valid, grounded in industry-relevant metrics for practical and measurable comparison. While small performance differences pose classification challenges, distinctions are supported by quantitative data, system specifications, and demonstrated potential. The magnetic levitation system exhibits characteristics of a reconfigurable manufacturing system, suitable for low-to-medium production volumes and rapid prototyping. This is supported by its overall throughput time of 4:45, process consistency with forming angles of 91.25° / 91.6° / 91.5°, and tolerances of ±1.57° / ±1.49° / ±1.35°, enabled by the flexible workpiece manipulation. In contrast, the galvo system demonstrates characteristics of a dedicated manufacturing system, achieving the fastest engraving cycle time of 0:02 and best engraving surface quality. However, it underperforms in forming, exhibiting angles of 91.95° / 91.8° / 91.75° with broader tolerances of ±1.24° / ±1.27° / ±1.44°, suggesting limitations in process versatility. The robotic system, reflecting traits of both dedicated and flexible manufacturing systems, demonstrates the highest consistency in forming with identical angles of 94.4° at all positions and tighter tolerances of ±1.27° / ±1.12° / ±1.17°, exhibiting traits of efficiency aligning with dedicated machinery. Although it records the longest throughput time (6:44) and poor engraving results, its adaptability and established multi-process capabilities suggest strong potential for flexible manufacturing applications.

5.1 Limitations of Magnetic Levitating Table

The current state of workpiece manipulation using magnetic levitation is primarily limited to handling small components, as it does not offer the same rigidity as conventional solid fixtures. Increasing the size or weight of the workpiece impacts the system's dynamic behaviour, necessitating more precise control to maintain high tolerances. Additionally, the system is constrained in certain degrees of freedom, particularly rotation around the X and Y axes (5°), due to magnetic field limitations. As a result, it cannot fully match the product flexibility of robotic systems. However, scalability is feasible within the specifications of the planar motor system, albeit these limitations should be considered.

5.2 Flexibility and Speed Trade-off in Mag-Lev Systems

The results indicate that the use of a magnetic levitation system presents a trade-off between speed and flexibility. In the experimental setup, the speed of the system lies between its competitors in terms of forming applications on the given low-volume scale. However, this trade-off can be reversed by introducing additional magnetic tiles and movers, enabling the simultaneous processing of multiple workpieces and enhancing overall system performance, gaining an advantage over compared systems.
From an industrial perspective, integrating flexibility into production systems offers a significant competitive advantage. Flexibility, defined as "the ability to neutralise the effect of demand uncertainty," is a fundamental principle of modern process system design [26, 27]. By leveraging the scalability of magnetic levitation technology, manufacturers can optimise both adaptability and throughput, aligning production systems with dynamic market demands.

5.3 Cost and Quality

In terms of product quality and tolerance adherence across the three processing technologies, the novel workpiece manipulation approach shows none to no measurable decline in performance as the tolerances lie in between the compared systems. The magnetic levitation table also demonstrates strong consistency across key quality metrics, indicating its industrial relevance as a viable processing technique. However, a critical factor requiring further investigation is the cost of production and per-unit manufacturing expense. While the system exhibits competitive performance in cycle time and processing speed, suggesting potential cost-effectiveness, a comprehensive economic analysis falls outside the scope of this study. From an industrial perspective, the proposed system demonstrates considerable potential as a promising option for dynamic low-volume production and rapid prototyping applications. Provided that the cost per unit remain acceptable, the system could deliver the hypothesised flexibility, speed and quality required by the sheet metal industry, thus addressing the identified gap highlighted in the literature review.

5.4 Further Works

Future research should explore cost implications and production scalability, focusing on applying the magnetic levitation table to industry-relevant products. This includes assessing product flexibility, quality, and fixation challenges using realistic workpieces. Emphasis should be placed on scaling production via individual moving fixtures and identifying design improvements to enhance system adaptability.

Conflicts of interests

The authors declare no conflict of interest concerning the research, authorship, and publication of this article.

Supplementary Material

Videos of experiments:
Robot: `https://youtu.be/xjrwrhWLSo4`
Galvo: `https://youtu.be/vQeoqomI0YU`
Mag-lev: `https://youtu.be/Dxf0CGlyItI`

References

[1] *Sheet Metal Market Size & Share, Industry Trends Report 2032.* Tech. rep. SNS Insider, May 2022. URL: `https://www.snsinsider.com/reports/sheet-metal-market-1474`.

[2] Serope. Kalpakjian, Steven R.. Schmid, and K. S. Vijay. Sekar. *Manufacturing engineering and technology.* Pearson Education Limited, 2023, p. 1312. ISBN: 9781292422244.

[3] William M. Steen and Jyotirmoy Mazumder. *Laser Material Processing.* 4th ed. Springer-Verlag London Limited, 2010, pp. 1–558. ISBN: 9781849960618.

[4] G. N. Nikolov et al. "Computer-aided process planning system for laser forming: from CAD to part". In: *International Journal of Production Research* 62.10 (May 2024), pp. 3526–3543.

[5] Qi Huang, Gunnar Kullberg, and Hans Skoog. "Sheet metal welding using a pulsed Nd: YAG laser-robot". In: (1994), pp. 3–23.

[6] Emmanuel Afrane Gyasi et al. "Prospects of Robot Laser Cutting in the Era of Industry 4.0". In: 10 (2022), pp. 639–655.

[7] Ravi Rao. *Gantry Systems: A Comprehensive Guide to Understanding and Implementing Gantry Technology*. 2023. URL: `https://www.wevolver.com/article/gantry-systems-a-comprehensive-guide-to-understanding-and-implementing-gantry-technology`.

[8] J. R. Lawrence, ed. *Advances in Laser Materials Processing: Technology, Research and Applications*. Elsevier Ltd., 2018, pp. 224–227. ISBN: 0081012527.

[9] Weixiang Wang, Lixin Wang, and Ning Guo. "Research and development of Nd:YAG laser engraving system". In: (Sept. 1996), pp. 207–212.

[10] Stevenson J.William. *Operations Management*. McGraw-Hill Education, 2015, pp. 236–259. ISBN: 978-0-07-802410-8.

[11] Slack Nigel, Brandon-Jones Alistair, and Johnston Robert. *Operations Management*. Pearson Education Limited, 2016. ISBN: 9781292098715.

[12] T. B. Lauwers, Z. K. Edmondson, and R. L. Hollis. "Free-roaming planar motors: Toward autonomous precision planar mobile robots". In: *Proceedings - IEEE International Conference on Robotics and Automation* 2004.5 (2004), pp. 4498–4503.

[13] *Robot Laser Application in Manufacturing*. URL: `https://dplaser.com/robot-laser-application-in-manufacturing/`.

[14] *The Wonder of Galvo Laser Machines*. URL: `https://omtechlaser.com/blogs/knowledge/the-wonder-of-galvo-laser-machines`.

[15] *Laser Galvanometers: Types & Applications Explained 2025*. URL: `https://opmtlaser.com/laser-galvanometers/`.

[16] Alessandro Ascari et al. "High speed laser cutting of ultrathin metal foils for battery cell production". In: 35 (2023).

[17] *KR FORTEC — KUKA AG*. URL: `https://www.kuka.com/en-de/products/robot-systems/industrial-robots/kr-fortec`.

[18] *Technical Data: BySprint Pro*. URL: `https://portalimages.blob.core.windows.net/products/pdfs/0ulvvh2t_BySprintProBroshure.pdf`.

[19] *XPlanar — Planar motor system — Beckhoff Automation*. URL: `https://www.beckhoff.com/da-dk/products/motion/xplanar-planar-motor-system/`.

[20] *BesCutter Mini Enclosed type Galvo 30W Laser Marking Machine*. URL: `https://bescutter.com/collections/galvo-laser-engravers/products/30w-galvo-fiber-laser-marking-machine-mini-enclosed`.

[21] Kai Wu and Bernd Kuhlenkoetter. "Dynamic behavior and path accuracy of an industrial robot with a CNC controller". In: *Advances in Mechanical Engineering* 14.2 (Feb. 2022).

[22] Alex Owen-Hill. "Job Shop vs Flow Shop: Can Robots Work for Both?" In: (2017). URL: `https://blog.robotiq.com/job-shop-vs-flow-shop-can-robots-work-for-both`.

[23] Abey Francis. *Flexible Manufacturing System - Definition, Process and Features - MBA Knowledge Base*. URL: `https://www.mbaknol.com/operations-management/flexible-manufacturing-technology/?`.

[24] AI Dashchenko. "Reconfigurable manufacturing systems and transformable factories". In: (2006), pp. 27–45.

[25] Jeff Morgan et al. "Industry 4.0 smart reconfigurable manufacturing machines". In: *Journal of Manufacturing Systems* 59 (Apr. 2021), pp. 481–506.

[26] Yash P Gupta and Sameer Goyal. "Flexibility of manufacturing systems: Concepts and measurements". In: *European Journal of Operational Research* 43 (1989), pp. 119–135.

[27] Marta Pérez Pérez, Ana María Serrano Bedia, and María Concepción López Fernández. "A review of manufacturing flexibility: systematising the concept". In: 54.10 (May 2016), pp. 3133–3148.

4. Statement of Intent

The scope of the project outlines a statement of intent focused on industrial relevance, addressing key gaps and system limitations. The objective is to assess whether magnetic levitation for laser processing can reduce costs, increase quality, and offer the flexibility needed for rapid prototyping or low-to-medium volume production.

4.1 Assessment of System Performance Across Different Product Scenarios

The problem analysis, Chapter 2, highlights the diverse requirements of the sheet metal manufacturing industry regarding efficiency, emphasising the need for a balance of these dimensions, with system flexibility being crucial to addressing the identified gap, alongside timeliness and cost-effectiveness. [31]
The assessment of the magnetic levitation system highlights its lack of industry relevance in terms of volume and product flexibility. To explore the potential and limitations of the magnetic levitation process system, interviews were conducted with relevant industry stakeholders, as documented in Appendix C and [34, 35]. These interviews identified three distinct production and product scenarios in which the magnetic levitation system could be applied, each representing a relevant use case for evaluating its industrial applicability. The first scenario explores the limitations of the system in the context of fast prototyping, focusing on lead time and fixation method design to accommodate diverse product features, sizes, and complexities. The second scenario examines the quality limitations of the system, focusing on tolerances, achievable standards, and the cost of poor quality, with insights from an established laser processing company. The third scenario focuses on the application of the system in a low-to-medium volume production, where the cost per produced unit is the element addressed. The industry-relevant part is elaborated and designed in Chapter 6 and illustrated in Figure 6.3.

4.2 Research Question and Thesis Objectives

Based on the problem analysis, the focus is to address the following research question:

How can component-level design and strategic approach of the magnetic levitation laser process system improve flexibility, quality, and cost in industrial applications?

To address the research question, objectives have been defined. These objectives are critical for guiding the research and ensuring that the system achieves the required performance and functional capabilities necessary to evaluate its industrial applicability.

4.2.1 Thesis Objectives

- *Design and develop a smart fixation or cutting technique to enhance product flexibility for industrial sheet metal manufacturing.*

Develop a fixation method or cutting technique to assess production limitations in volume and flexibility. A model is developed to project throughput, with success defined by autonomously producing 4 features, a cycle time under 10 [s], and a throughput time of ≈ 7 [min].

- *Assess the impact of system flexibility on quality, examining tolerances, achievable standards, and implementing a model to assess the cost of poor quality.*

Develop a quality assessment method to evaluate tolerances and integrate it into a cost-of-poor-quality model. Success is defined by meeting industry standards and reducing quality costs through system flexibility.

- *Evaluate the applicability of the magnetic levitation process system for low-to-medium batch production, with a focus on cost per unit and production efficiency.*

Develop an evaluation method, including a cost model, to determine the cost per unit. Success is measured by whether the cost per unit remains constant or declines, ensuring the system's competitiveness with conventional manufacturing for low-to-medium production volumes.

5. Requirements

Building on the literature and defined objectives, the product scenarios serve as the foundation for the engineering requirements. The system's relevance is assessed by its ability to meet these industry-driven specifications. This section outlines the methodology, rationale, and evaluation process, followed by a summary table of the engineering specifications.

5.1 Methodology for Requirements

The methodology outlines the selection of requirements, starting with industry relevance, followed by a scenario-based approach to define specifications, and concludes with a strategy for evaluating the system.

Industry Engagement

To enhance the industrial relevance of the system, the methodology applied in this requirements section involves close collaboration with relevant industry stakeholders seen in Appendix C and [34, 35]. This approach is chosen to ensure that the proposed system aligns with real-world requirements and challenges. The primary objective is to evaluate whether the developed system can meet these industry-specific requirements, thus ensuring its relevance and applicability in a low-to-medium volume production or a rapid prototyping environment. This is especially concerning flexibility and time efficiency, as these are some of the more important criteria for a manufacturing company.

Product Scenario Based Approach

This methodology employs a product scenario-based approach to ensure industrial relevance and general applicability, as introduced in Chapter 4. Three distinct scenarios are used to address the thesis objectives, identify system limitations, and assess its industrial potential. To support this, targeted questions are sent to stakeholders to gather quantifiable data, which informs the engineering specifications by aligning the system with industry standards, stakeholder requirements, and acceptable defect rates seen in Appendix C.

Evaluation Process

For the methodology to remain relevant, an evaluation of the proposed system is essential. This evaluation is carried out by manufacturing the assessment part, which Chapter 6 explains in detail. The system produces a series of these assessment parts to evaluate its flexibility in terms of volume and product variety, cost efficiency, and adherence to quality standards. The manufacturing system is assessed against the three defined objectives, with each objective having its relevant engineering specifications.

5.2 Engineering Specifications

Each section starts with a brief description of the area of focus before outlining the related requirements. Table 5.1 presents the requirements related to product flexibility and strategic approach, focusing on the capability of the manufacturing system to accommodate product variation and the constraints associated with production volume. Some of the requirements are drawn from sources [34, 35] and interviews with industry stakeholders C.

Flexibility and Strategic Approach

No.	Requirement	Value	Direction	MoSCoW	Source
1.1	*Product size support (standardised part envelope)*	100×100 mm	–	Must	[34]
1.2	*Material thickness range supported*	0.2–0.6 mm	↑	Must	[34]
1.3	*Maximum bend angle (stakeholder demand)*	180°	–	Will not	[34]
1.4	*Capability to support distinct feature variations*	4	↑	Must	Fig: 6.2
1.5	*Target order size (average production volume per job)*	2,000	↑	Could	App: C

Table 5.1: Flexibility-related requirements and associated prioritisation. Project-defined requirements, labelled "-", are based on industry expectations and feasibility assessments.

Table 5.1 summarises the flexibility-oriented design requirements for the system. These encompass the capability to accommodate variation in product features and batch sizes, while maintaining compatibility with standardised workpiece dimensions and a defined range of material thicknesses. The prioritisation follows the MoSCoW method, guiding the design direction with respect to strategic flexibility. MoSCoW analysis is a prioritisation technique that helps establish a shared understanding of the significance assigned to each requirement. The acronym MoSCoW stands for Must have, Should have, Could have, and Won't have. [63]

Table 5.2 presents the requirements associated with time efficiency and production throughput. These parameters directly influence the system's operational cost and responsiveness, both of which are essential for meeting commercial demands in dynamic production environments. Some of the engineering specifications, particularly those related to cycle time and throughput time, are derived from benchmarks observed in industrial bending systems, ensuring that the system's performance aligns with established production standards within the sheet metal industry.

Time Efficiency

No.	Requirement	Value	Direction	MoSCoW	Source
2.1	*Transition time between distinct processing features*	10 s	↓	Would	App: C
2.2	*Cycle time (time per individual processing task)*	10 s	↓	Must	App: C
2.3	*Throughput time (total time per finished unit)**	≈ 7 min	↓	Must	-

Table 5.2: Production efficiency and time-related requirements. Project-defined requirements, labelled "-", are based on industry expectations and feasibility assessments. *Requirement based on a comparable part manufactured using a press brake (20 x (10+10) seconds).

Table 5.3 details the quality-driven performance expectations, which are derived from industrial benchmarks and stakeholder inputs as those stated in Appendix C and [34, 35]. These include tolerances, permissible bend angles, and defect rates, all of which serve as indicators of process capability and repeatability in high-volume manufacturing contexts.

Quality

No.	Requirement	Value	Direction	MoSCoW	Source
3.1	*Minimum achievable bend radius*	1 mm	↓	Could	-
3.2	*Bend angle must be uniform along its length, varying by a set value*	±1°	↓	Must	-
3.3	*Tolerance range of current process*	±1°	↓	Must	-
3.4	*Maximum permissible defect rate*	5%	↓	Would	App: C
3.5	*CoPQ must not exceed an acceptable share of total production cost*	5%	↓	Must	[36]
3.6	*Should reduce CoPQ compared to conventional methods*	≥ 20%	↑	Should	-

Table 5.3: Quality-related requirements and prioritisation. Project-defined requirements, labelled "-", are based on industry expectations and feasibility assessments.

Table 5.4 outlines the economic aspects of production and tooling, serving as a benchmark against conventional manufacturing and supporting the financial assessment of the proposed system. Engineering specifications are based on a 10-year system depreciation and immediate tooling depreciation per produced batch. These influence production costs, held against a benchmark price inquiry at a "one stop shop" quoting 100 DKK per part, "Xometry". To ensure the system remains competitive and provides a compelling incentive for industrial stakeholders. The total cost should be lower than that of conventional dedicated manufacturing systems.

Cost and Tooling

No.	Requirement	Value	Direction	MoSCoW	Source
4.1	*Tooling cost (fixation or cutting technique)*	50–80,000 DKK	↓	Must	[34]
4.2	*Lead time*	4 weeks	↓	Could	[34]
4.3	*Production cost per unit**	100 DKK	↓	Must	-
4.4	*Total cost of the production system***	≥5% reduction	↑	Must	-

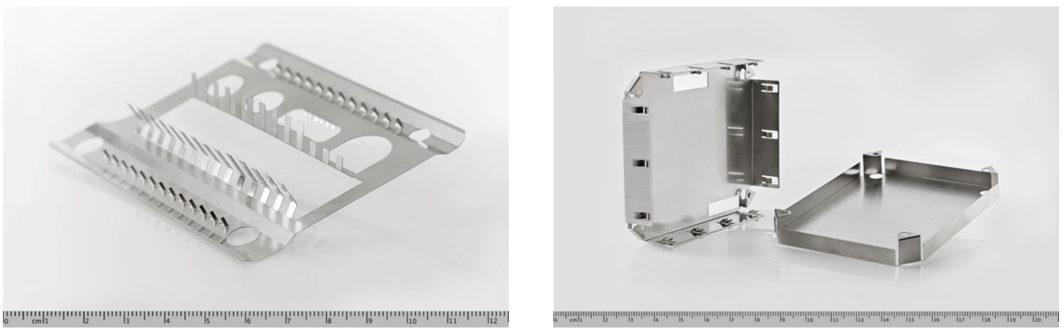
Table 5.4: Economic requirements for production and tooling. Project-defined requirements, labelled "-", are based on industry expectations and feasibility assessments. *Based on inquiry from a one-stop shop manufacturer, "Xometry". ***Reduction in price compared to a dedicated manufacturing system.

6. Fixture Approach and Manufacturing Methodology

Before designing the fixation, a clear approach for addressing the first objective must be established. This approach is influenced not only by the defined objectives but also by the specific product features that the laser system is required to replicate. Two alternative approaches are proposed and evaluated to determine which offers the greatest potential for fulfilling the objective. Following this, the manufacturing and measurement of the assessment part are presented to highlight early-stage manufacturing errors and to demonstrate the empirical development of processing parameters and practices aimed at improving production quality.

6.1 Product and Features

Inspiration for the products and features replicated on the laser setup is drawn from the industries identified in the literature studies, with a particular focus on the electronics sector. The examples shown in Figure 6.1 are based on commercially manufactured components from COVI Precision, a company operating within the sheet metal industry and one of the industrial stakeholders consulted during the project. This approach ensures that the features selected for replication are grounded in real-world industrial relevance and reflect current market demands for flexibility and quality in thin-sheet production.



(a) Example product 1. **(b)** Example product 2, electronics shielding.

Figure 6.1: Products manufactured by COVI Precision used as a source of inspiration. [64]

From the products illustrated in Figure 6.1 features within the thin sheet metal industry can be extracted. From these products, common features are sketched in Figure 6.2 and arranged from simplest to complex to recreate the proposed magnetic levitation system.

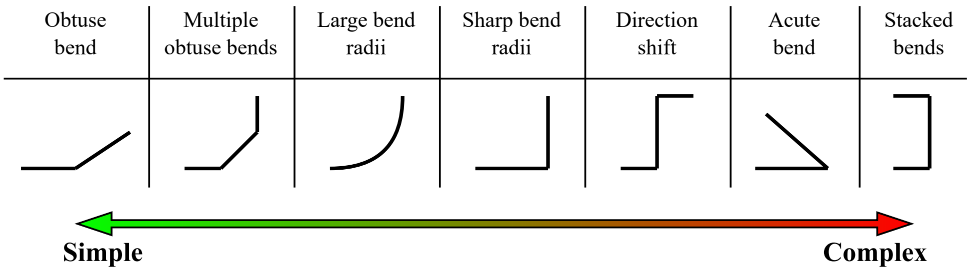
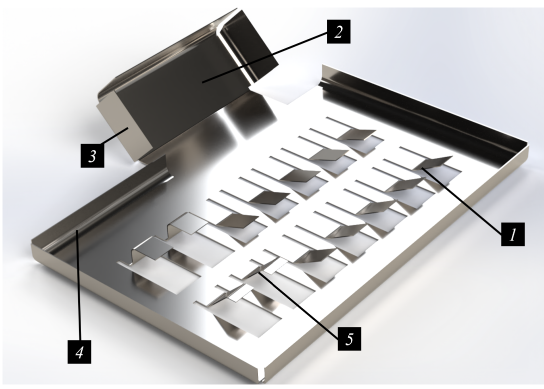
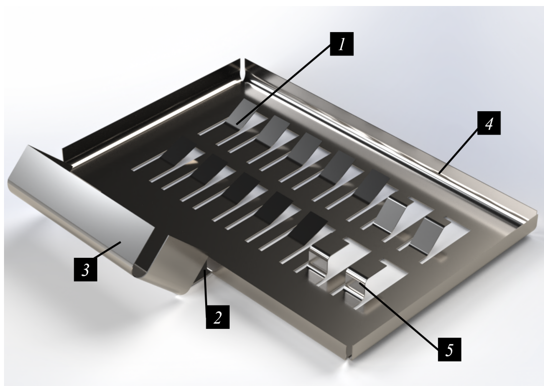


Figure 6.2: Classification of bend features, arranged from simplistic to most complicated.

As illustrated in Figure 6.3, the assessment part is designed with repeated features to evaluate quality through repeatability, while volume flexibility is examined through theoretically scaled-up systems, which are then used to assess cost performance. It serves as a representative test component for demonstrating the system's flexibility while assessing its overall impact on both quality and cost. The results are then evaluated against the engineering requirements presented in Chapter 5.



(a) Seen from the right.



(b) Seen from the left.

Figure 6.3: Conceptual design of assessment part constructed to incorporate the identified bend classifications. 1: Obtuse bend, the part contains one row of identical 35 degrees and a row of bends increasing from 15 to 90 degrees. 2: Multiple obtuse/stacked bends. 3: Large bend radii. 4: Sharp bend radii. 5: Direction shifting bends 45 and 90 degrees.

6.2 Fixation Approaches

As outlined in the research question, design modifications are introduced at the component level, specifically through the development of new fixation strategies aimed at enhancing both volume and product flexibility. The two proposed approaches differ fundamentally in their methodology: one focuses on designing a more complex, adaptive fixture to accommodate a wider range of geometries, while the other leverages established manufacturing techniques through a smart, standardised fixation concept that simplifies implementation without compromising flexibility.

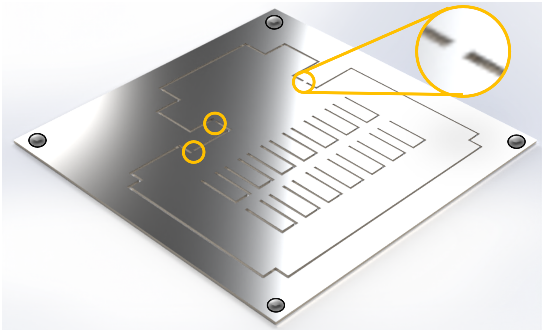
6.2.1 Approach 1

The first approach focuses solely on designing a fixture capable of securing products with the identified features, from Figure 6.2. A significant drawback is that the workpieces change shape or geometry during processing. This must be considered when determining fixation points, either by employing a loose fixation method or by releasing and refitting the workpiece multiple times during processing. Ultimately, this introduces unpredictable tolerances, which can negatively impact quality and directly conflict with the research objective. Refitting the part during processing may lead to deviations in placement relative to its original position, thereby affecting the consistency and accuracy of the processing outcome. This fixture must therefore be highly flexible, potentially incorporating numerous moving parts to accommodate varying geometries and enhance product adaptability. However, this approach does not influence the process generally, meaning that it can draw benefits from the existing routing and mix flexibility. The pros and cons are listed below:

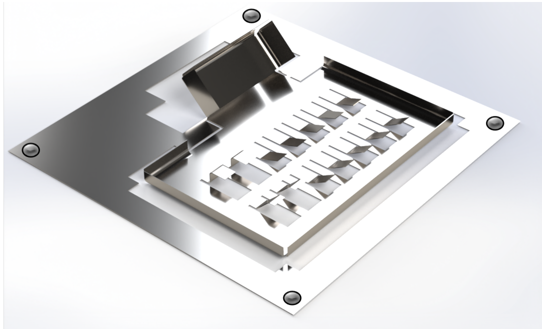
- **Pros**
  - Possible higher product flexibility
  - Utilisation of mix flexibility
  - Utilisation routing flexibility
- **Cons**
  - Moving parts and actuators
  - Re-fixation (Poor tolerances)
  - Complex fixture needed

6.2.2 Approach 2

The second approach introduces a degree of standardisation by using precut templates before fixation, as illustrated in Figure 6.4a. This method requires an extra step made on either the same or a different laser before forming can occur, which can cause implications regarding routing flexibility as the setup becomes more restricted. While this method allows for a simpler fixture design, it may limit product flexibility since the product size cannot exceed the boundaries of a predefined mounting flange. The mounting flange also serves as a permanent fixation point, eliminating the need to refit the workpiece during processing, as shown in Figure 6.4b. Due to this standardisation, the fixture requires less flexibility, making it easier to design and potentially more cost-effective. The pros and cons are listed below:



(a) Flat template of a workpiece with some remainder left uncut as fixation points (marked in orange).



(b) Workpiece is bent while still attached to the template.

Figure 6.4: Example of a product resembling an electronics shielding box, manufactured according to the 2^{nd} approach.

- **Pros**
  - Cheaper fixture
  - Increase tolerances
  - Easier production
  - Low lead time
  - Scalability of product
- **Cons**
  - Preparation needed
  - Limiting Product flexibility
  - External process or routing
  - Material wasted

6.2.3 Selection

The most suitable approach is selected using a decision matrix, as shown in Table 6.1, based on quantifiable statements derived from the research objectives. [37] These statements are general and not rooted in specific engineering specifications, serving only as a starting point for addressing the stated problem.
The two approaches are then evaluated against each other using a simple five-level scale, assessing how well each approach aligns with the statements and the extent of its impact.

Decision Matrix for Approach Selection

Statement	Description	Approach 1	Approach 2
Can replicate all 6 classified bends	*Capability to produce all required bend types*	SA	SA
Can achieve high tolerances	*Ability to meet precision requirements of bends*	D	SA
Ease of scaling in volume	*Ability to scale production efficiently*	A	A
Ease of incorporating new products	*Flexibility in handling design variations*	D	A
Cost-effective at low-medium volume	*Feasibility for small-to-mid production scales*	N	A
Capable of fast cycle time	*Efficiency in processing speed*	N	N
Does not conflict with existing routing flexibility	*Compatibility with routing configurations*	SA	SA
Does not conflict with existing mix flexibility	*Ability to handle product mix variations*	N	SA
Does not conflict with existing expansion flexibility	*Scalability without major constraints*	D	D
SUM		2	10

Table 6.1: Decision matrix for selecting Approach 1 or 2 based on their influence on key criteria derived from research objectives. **Legend:** SA – Strongly Agreed (+2), A – Agreed (+1), N – Neutral (0), D – Disagreed (-1), SD – Strongly Disagreed (-2).

The decision matrix favours approach 2 in the majority of the statements. Based on this, approach 2 will be selected as the approach to design the fixture.

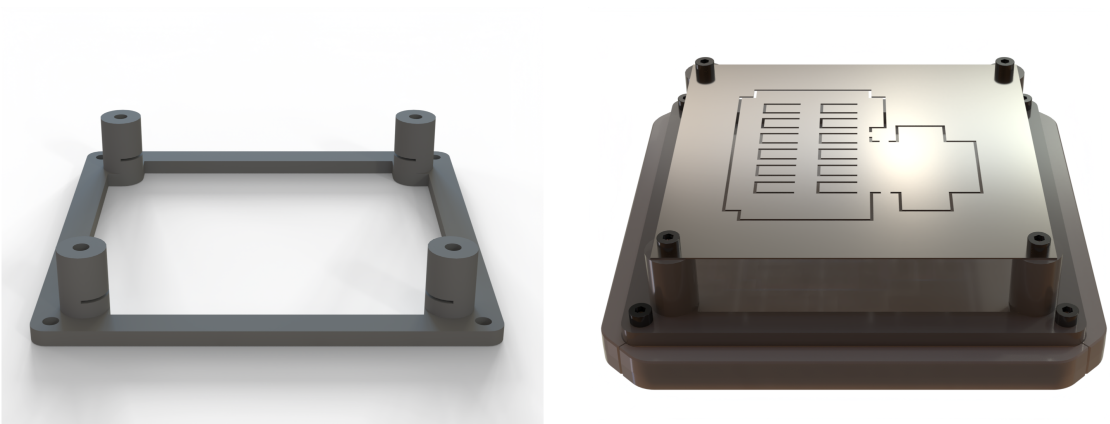
6.3 Fixture Design

The fixture design commences by defining the outlying constraints regarding the mounting flange. This constraint is set by the size of the Beckhoff magnetic mover (max size) and the available workspace on the experimental setup of one tile (min size). Therefore, the dimension for the mounting flange is set between these constraints as seen in Table 6.2.

Description	Dimensions
Mover Mounting Holes (max size)	140x140 mm
Assessment Part Mounting Flange	120x120 mm
Available Workspace (min size)	80x80 mm

Table 6.2: Dimensions

The mounting flange is secured to the fixture through four holes in each corner, aligning with holes in the fixture as shown in Figure 6.5 that are bolted together. The fixture is 3D printed with a slot that allows for a sheet of metal to be inserted as a shield between the work area and the mover. This is for the protection of the mover when laser forming.



(a) 3D printed fixture. **(b)** Fixture assembly.

Figure 6.5: Fixture and complete assembly of Beckhoff mover, fixture and assessment part.

6.4 Manufacturing the Assesment Part

This section covers how the assessment part is manufactured on the experimental setup, shown in Figure 6.6, and how the process parameters are empirically identified.

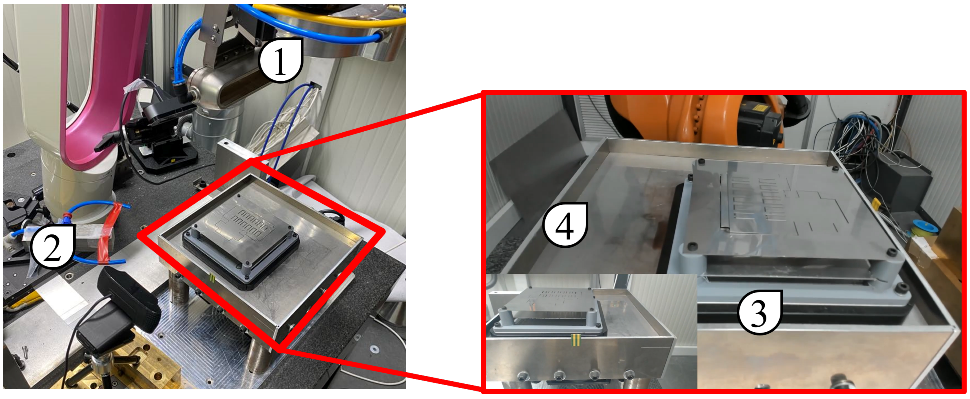


Figure 6.6: The experimental setup. 1: The laser tool head. 2: Compressed air supply for cooling. 3: Fixture mounted on XPlanar mover. 4: XPlanar tile. Link to video `https://youtu.be/DSIt6erkAvM`

6.4.1 Process parameters

The process parameters are found through a series of initial tests on small blanks of 40 x 100 x 0.5 [mm], with the objective to determine the power, speed needed and the required scan lines to achieve a desired bend as seen in Appendix B. First, the speed is determined, which is done by calculating the Fourier number, (6.3), dictating the type of thermal deformation. In this case, the TGM is desired.

$$F_0 < 1 \quad \text{The TGM is dominant} \tag{6.1}$$

$$F_0 > 1 \quad \text{The UM or BM is dominant} \tag{6.2}$$

$$F_0 = \frac{\kappa d}{t^2 v} \tag{6.3}$$

Here, κ denotes the thermal diffusivity, d the laser beam diameter, t the material thickness, and v the laser scan speed. Note that laser power does not enter Equation (6.3), so it does not dictate which bending mechanism predominates. It does, however, affect the extent of deformation, increasing the laser power yields a larger effect of the mechanism.

κ	d	t	v
4.2 $[m^2\, s^{-1}]$	0.27 $[mm]$	0.5 $[mm]$	$5 - 50\, [m\, s^{-1}]]$

Table 6.3: The parameters used to calculate the Fourier number, note that the scan speed is given as a range, this is the permissible range yielding the desired mechanism.

Inserting the parameters presented in Table 6.3 into (6.3) gives a $F_0 < 1$ from the inserted scan speeds; the fastest is chosen at 50 $[mm/s]$.
The power is determined by starting at 200 $[W]$ and decreasing until minimum heat distortion can be seen on the underside of the bend. Satisfactory results were achieved at 100 $[W]$, where a bend angle per pass is recorded as seen in Table 6.4.

Radii	**Angle per scan [°]**	**Scan lines to 90°**
5 mm	2.5	39
2 mm	2.2	42
1 mm	2.0	45

Table 6.4: Bend angle per scan at different radii.

Not all targeted bend shapes shown in Figure 6.2 can be produced by TGM, as it always yields an upward curvature. To achieve a downward bend, the buckling mechanism should be used, but with metals, this approach is impractical, as the part would overheat and melt before it could buckle downward. This means that the part has to be released from the fixture, and flipped over, and then re-clamped to bend in the opposite direction. However, this extra handling undermines the core advantage of the chosen approach, which was intended to eliminate any need for repositioning the part.

6.4.2 Forming Instruction

Once the process parameters have been established, the sequence of manufacturing steps can be defined. Based on the CAD drawing of the assessment part, the location of each bend is identified to generate the corresponding coordinates for the G-code instructions, as illustrated in Figure 6.7. The number of scan lines required per bend is determined by the angle induced per scan, which has been established empirically. These findings are further detailed in Appendix B.

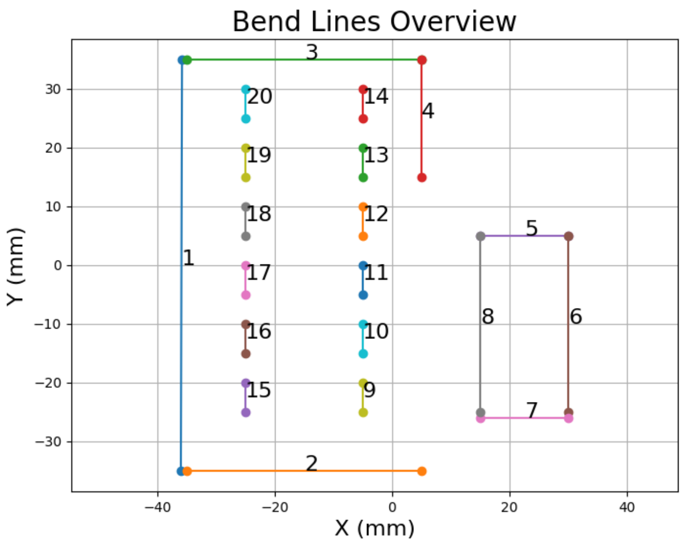


Figure 6.7: Bend passes with their respective number.

Bend	Angle [°]	Radii [mm]	Passes	Power [W]	Speed [mm/s]
Bend 1	90	2	43	100	50
Bend 2	90	2	43	100	50
Bend 3	90	2	43	100	50
Bend 4	90	2	43	100	50
Bend 5	90	2	43	100	50
Bend 6	90	2	43	100	50
Bend 7	90	2	43	100	50
Bend 8	45	5	21	100	50
Bend 9	35	2	16	100	50
Bend 10	35	2	16	100	50
Bend 11	35	2	16	100	50
Bend 12	35	2	16	100	50
Bend 13	35	2	16	100	50
Bend 14	35	2	16	100	50
Bend 15	15	1	8	100	50
Bend 16	30	1	15	100	50
Bend 17	45	1	23	100	50
Bend 18	60	1	30	100	50
Bend 19	75	1	37	100	50
Bend 20	90	1	47	100	50

Table 6.5: Laser bending parameters for the 20 bends.

A Python script is developed to translate the contents of Table 6.5 into g-Code instructions that can be executed by the Beckhoff PLC. [65]

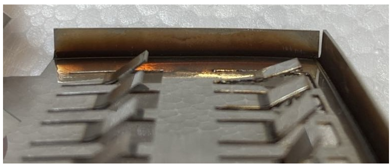
6.4.3 Initial Tests

Initial tests are conducted to verify the correct translation of the generated G-code instructions and to evaluate the resulting geometry of the assessment part using the first empirically determined process parameters. A key observation from these tests is the importance of dwell time between passes, which proves critical for achieving the desired bend angle and minimising unwanted warping. However, dwell time also emerges as the primary contributor to the overall processing time, as shown in Table 6.6.

Process	**Dwell Time 3 [s]**	**Dwell Time 6 [s]**	**Dwell Time 8 [s]**
Bending	4 min 02 s	4 min 02 s	4 min 02 s
Travel	2 min 57 s	2 min 57 s	2 min 57 s
Cooling	28 min 24 s	56 min 48 s	75 min 44 s
Total	**35 min 23 s**	**63 min 47 s**	**82 min 43 s**

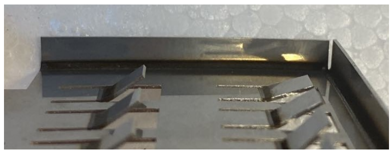
Table 6.6: Total process time for varying dwell durations. Cooling time increases with dwell time, while bending and travel remain constant.

These dwell durations are tested to see what dwell duration is feasible for a satisfactory result regarding heat distortion and warping; these tests are illustrated in Figure 6.8 and 6.9.



(a) 3 second dwell.

(b) 6 second dwell.



(c) 8 second dwell.

Figure 6.8: Comparison of bend line 2 with different dwell durations. No difference in heat distortion between 6 and 8 seconds dwell duration.

Figure 6.9: Warping of assessment part seen against a flat surface. No difference in warping between 6 and 8 seconds dwell duration. However still significant warping.

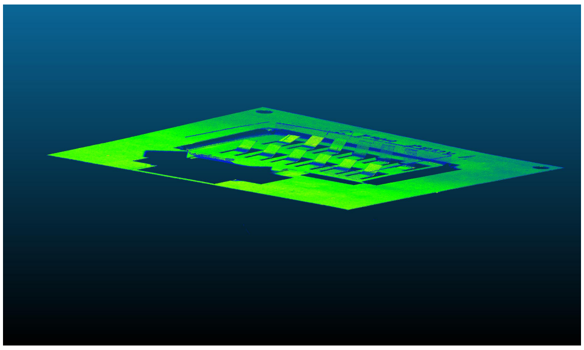
From Figure 6.8 it can be seen that increasing the dwell duration beyond 6 seconds has no effect on the heat distortion, as no further reduction in discolouring on the metal is observed. Likewise, in Figure 6.9, increasing the dwell duration will not further reduce warping; however, significant warping is still present.
A final attempt to reduce warping is carried out by modifying the sequencing of the bend passes. Rather than completing each bend individually, the instructions are generated to group bends 1–4, executing one scan line on each before proceeding to the next pass. Additionally, scan lines are applied in alternating directions. This approach aims to examine whether the resulting thermal stresses can be redistributed

more evenly across the plate, thereby counteracting the tendency for lopsided warping and improving structural stiffness. As a further refinement, all inner scan lines are prioritised at the beginning of the sequence. This allows the sheet metal to stabilise and "set" itself before the outer bends are formed.
The combination of grouped execution, alternating directions, and bend prioritisation results in a significant reduction of warping, but did not eliminate it, as seen in Figure 6.10. In addition, this approach proved to be faster compared to the second column in Table 6.6 as the travel time is reduced by 50 seconds.

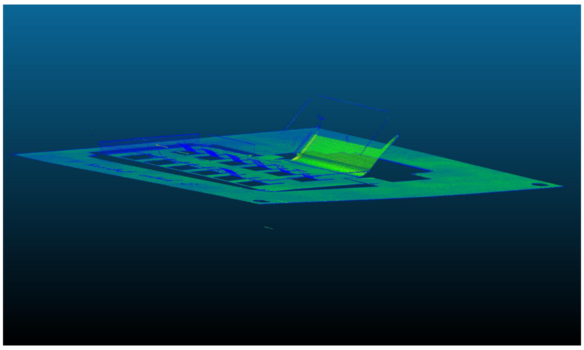
Figure 6.10: Test conducted with new bend pass sequence, less warping can be seen against the flat table.

6.5 Measuring the Assessment Part

Following the manufacturing of the assessment part, precise measurement is required to evaluate its geometric quality. Due to its complexity and multiple intricate bends, traditional tools such as protractors are inadequate. Instead, a 3D scanning method is used to generate a point cloud, as shown in Figure 6.11 and 6.12. This enables the extraction of key geometric features, bend angles, radii, and angular uniformity, through a systematic and repeatable process, minimising human error.

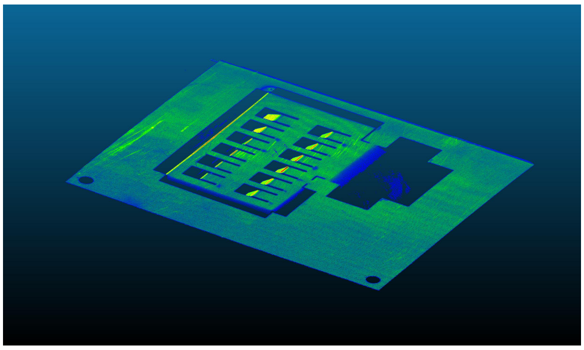


(a) Scan 1 – Top view (angled)

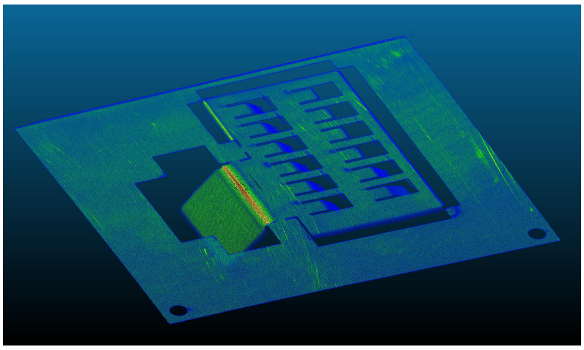


(b) Scan 2 – Top view (different orientation)

Figure 6.11: 3D scan outputs – top view of the assessment part from different angles.



(a) Scan 3 – Bottom view (angled)



(b) Scan 4 – Bottom view (different orientation)

Figure 6.12: 3D scan outputs – bottom view of the assessment part from different angles.

A brief explanation of the measurement pipeline is provided to clarify how bend angle, bend radii, and angular uniformity are extracted. The project group contributed only to scanning the part and generating the CAD model for alignment. As shown in Figure 6.13, the process begins by loading the 3D scan data, meshing the CAD model, and aligning it with the scan. This enables accurate cropping and noise reduction. A multi-order RANSAC algorithm is then used to extract planar segments and identify usable bends. A region growing algorithm calculates surface normal variance, and a custom arc length detector determines the arc length of each bend. This pipeline ensures consistent and reproducible results.

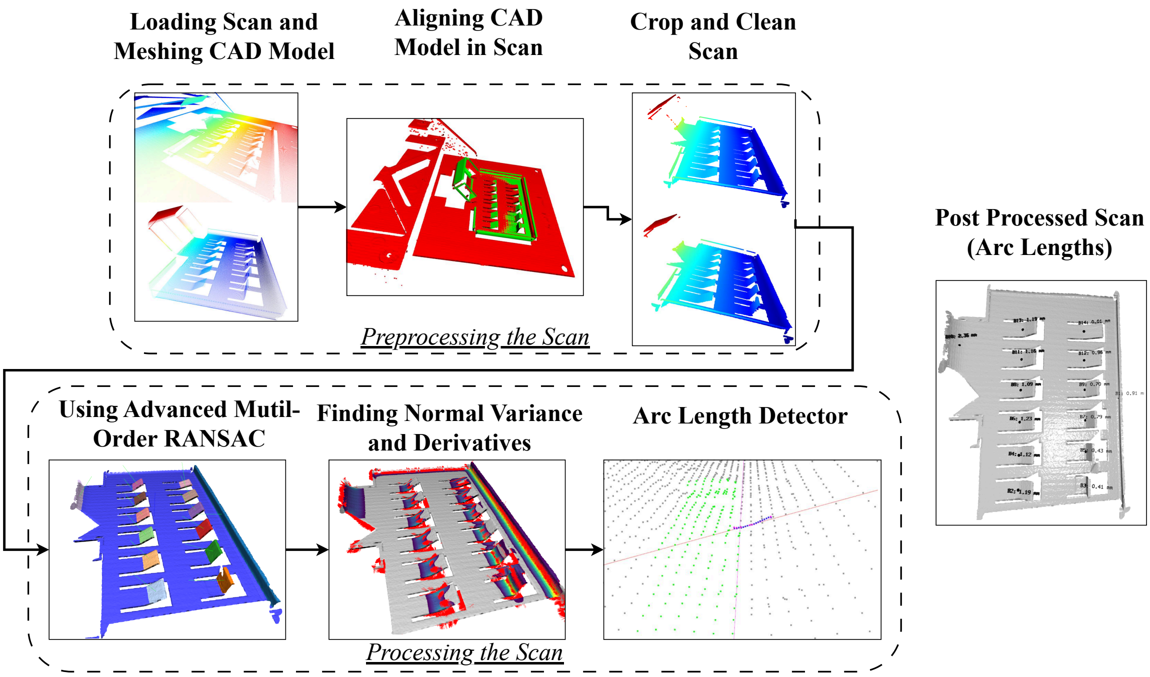


Figure 6.13: Visual representation of the measurement pipeline showing the key stages involved in preprocessing, processing, and post-processing. The figure complements the descriptive methodology by illustrating the data flow and applied tools used to extract geometric bend features.

The results obtained from the measurement pipeline are summarised in Table 6.7. The table presents the mean bend angle across the five scanned assessment parts, the deviation from the intended bend angle, the minimum measured bend radius, and the deviation from the specified bend radius. These metrics provide a quantitative basis for evaluating the accuracy of the empirically found parameters of the laser forming process.

Bend	**Mean Angle [°]**	**Deviation [°]**	**Minimum Radii [mm]**	**Deviation [mm]**
Bend 1	83.83	6.17	0.62	1.38
Bend 8	38.06	6.94	2.41	2.59
Bend 9	32.91	2.10	2.09	-0.09
Bend 10	32.86	2.14	1.00	1.00
Bend 11	32.42	2.58	0.70	1.30
Bend 12	32.25	2.75	0.90	1.10
Bend 13	32.02	2.98	2.04	-0.04
Bend 14	31.86	3.14	2.18	-0.18
Bend 15	15.65	-0.65	3.60	-2.60
Bend 16	27.60	2.40	1.80	-0.80
Bend 17	40.30	4.70	0.95	0.05
Bend 18	52.02	7.98	0.53	0.47
Bend 19	63.66	11.34	0.35	0.65
Bend 20	78.08	11.92	0.30	0.70

Table 6.7: 3D scan measurement of the assessment part, bends 2-7 are excluded due to inadequate measurement points during scanning.

Throughout the measurement process, three primary sources of error are identified: manufacturing inaccuracies, scanning noise, and scan processing errors. Manufacturing-related deviations refer to how closely the physical part aligns with the CAD ground truth, particularly whether the scan lines originate from the intended regions. Scanning errors arise from surface noise and variations in scan angle precision, which can influence the consistency and accuracy of the captured geometry. Lastly, processing errors are associated with the algorithms used to extract geometric features such as bend angles. As previously discussed, warping is observed in all parts, which introduces localised distortion during the multi-order RANSAC fitting. Since the warped surface serves as the reference plane for angle calculations, such deformations can cause slight variations in angle estimation from scan to scan and part to part. The RANSAC tolerances used to compensate for deviations are presented in Table 6.8:

Part	RANSAC Tolerance [mm]
Part 1	0.40
Part 2	0.60
Part 3	0.50
Part 4	0.60
Part 5	0.57

Table 6.8: RANSAC tolerance values used for geometric curve fitting of each scanned assessment part. Lower values indicate a tighter fit and more consistent geometry.

These tolerances indicate that the degree of warping is relatively consistent across parts. However, they also suggest that deviations in calculated angles may, in part, result from limitations in the processing algorithm's ability to compensate for surface irregularities. This reinforces the importance of considering both measurement noise and algorithmic robustness when evaluating geometric consistency.

6.5.1 Summery

In summary, approach two has been identified as the most effective approach for enhancing various flexibility dimensions within the system. Controllable process parameters, such as laser power and scan speed, were set at 100 [W] and 50 [mm/s], respectively. The dwell duration between successive passes plays a critical role in allowing sufficient cooling, thereby ensuring consistency in the bend angle per pass. Additionally, by strategically sequencing the bending passes to distribute thermal stress evenly, the risk of part warping can be reduced but not eliminated. Based on the selected approach and parameter configuration, the total processing time for a part is estimated to be approximately one hour. A limitation of the TGM approach is its inability to produce downward bends, as it inherently yields upward curvature. To achieve downward bending, the part must be released from the fixture, flipped, and re-clamped, which introduces additional handling and reduces the advantage of eliminating repositioning. To assess geometric quality, a 3D scanning-based measurement pipeline was employed, enabling the extraction of key bend metrics including angle, radii, and angular uniformity. This non-contact method ensures repeatability and mitigates human error, though some variation arises due to manufacturing deviations, surface noise, and limitations in scan processing algorithms. Based on these findings, five parts are produced for evaluation against engineering specifications and thesis objectives.

7. Results and Evaluation

Based on the established processing instructions and the defined evaluation framework, manufactured assessment parts are evaluated against the relevant engineering specifications. The purpose is to determine the degree of compliance and effectiveness of the system. Subsequently, the system is evaluated in accordance with the project objectives to assess its potential for enhancing product and volume flexibility in industrial applications. The evaluation process addresses the stated objectives sequentially: alignment with Industry 4.0 principles, such as modularity and real-time capabilities, and KPIs (Key Performance Indicators), assessment of product quality relative to customer requirements, and an analysis of industrial feasibility in terms of production volume capabilities and cost competitiveness.

7.1 Objective 1: Product Flexibility and Industrial KPIs

The first objective focuses on evaluating the system's performance in relation to Industry 4.0 principles, particularly its flexibility, as well as its alignment with KPIs. This evaluation is closely linked to the selected manufacturing approach, discussed in Chapter 6, as different strategic approaches yield varying outcomes regarding Industry 4.0 compliance and the ability to meet standards within the sheet metal industry. Approach Two is selected based on its demonstrated potential within the decision matrix, showing favourable alignment with the criteria for flexibility, processing speed, and quality. This involves the use of a precut template that introduces metal flanges to enhance standardisation while maintaining the desired level of flexibility. As outlined in Chapter 4, specific success criteria have been established to assess whether the system represents a viable solution for either production or R&D within the sheet metal industry. The key criteria are derived from the research objectives, the success criteria outlined in Chapter 4, and the associated engineering specifications. These criteria represent the most critical requirements, and their fulfilment serves as a basis for determining whether the system warrants further investigation and development:

- **Cycle Time:** Measurement of the time required to complete individual processing tasks, such as a single bend operation.
- **Throughput Time:** Assessment of the total time taken to manufacture a complete part from start to finish, including bending, cooling, and transport.
- **Distinct Feature Variations:** Evaluation of the system's ability to accommodate multiple geometric features, reflecting its product flexibility.

With the primary criteria established, the results obtained from producing five assessment parts using the magnetic levitation laser processing system are compared against the engineering requirements outlined in Tables 5.1 and 5.2, concerning flexibility and time efficiency. The table with the requirements relevant for thesis objective one is revisited in Table 7.1.

Requirements (Flexibility and Time Efficiency)

No.	Requirement	Target Value	Direction	MoSCoW
1.1	*Capability to support distinct feature variations*	4	↑	Must
1.2	*Target order size (average production volume per job)*	2,000	↑	Must
1.3	*Product size support (standardised part envelope)*	100x100 *mm*	–	Could
1.4	*Material thickness range supported*	0.2–0.6 *mm*	↑	Must
2.1	*Cycle time (time per individual processing task)*	10 *s*	↓	Must
2.2	*Throughput time (total time per finished unit)*	7 *min*	↓	Must
2.3	*Transition time between distinct processing features (shift time)*	10 *s*	↓	Would

Table 7.1: Flexibility and time efficiency requirements used for evaluation.

The experimentally observed outcomes corresponding to the defined flexibility and time efficiency criteria are presented in Table 7.2. This table serves as the basis for assessing and calculating the system's performance relative to the predefined requirements:

Experimental Results (Flexibility and Time Efficiency)

No.	Parameter	Observed Value
1.1	*Distinct supported feature variations*	4
1.2	*Target order size (average production volume per job)**	≈ 2,000
1.3	*Supported Product size*	100x100 *mm*
1.4	*Material thickness range supported*	0.5–1 *mm*
2.1	*Cycle time (time per individual processing task)***	318 *s*
2.2	*Throughput time (total time per finished unit)*	64 *min* 8 *s*
2.3	*Transition time between distinct processing features (shift time)*	1 *s*

Table 7.2: Observed performance of the experimental system in relation to flexibility and time efficiency. *Assessed on the experimental setup and a theoretical larger production setup. **For the longest bend, bend 1 in Figure 6.7.

The results confirm that the system supports the required four simplest feature variations from Figure 6.2, demonstrating the necessary flexibility for rapid prototyping. Although some bend types are excluded due to manual handling requirements, directional bends should be achievable by reorienting the part mid-process. The target order size is theoretically validated through calculations presented later in this section. The system supports the standardised product envelope and can process material thicknesses above the specified range; however, parts thinner than 0.5 [mm] were not tested, leaving the lower bound unverified. The observed cycle and throughput times exceed requirements due to single-part processing, though estimates for scaled-up production are provided later. Overall, the system presents a viable alternative to conventional manufacturing systems for rapid prototyping and low-volume agile manufacturing.

To assess the system's competitiveness for low production volumes ($\approx$ 2,000 units) from Table 7.1, a model is developed to estimate the achievable output within a 24-hour period. The initial calculation of the unit output within a 24-hour period is conducted using the experimental setup consisting of a single tile and one mover, seen in Figure 6.6. The following formula defines the model:

$$\text{Units} = \left(\frac{24\,\text{hr} \cdot \text{Utilisation Rate}}{\text{Throughput time}}\right) \cdot (1 - \text{Error Rate}) \tag{7.1}$$

In Equation (7.1), the utilisation rate (in %) represents the proportion of time that is classified as value-adding to the processing, while the throughput time denotes the duration required to complete one assessment part. The error rate (in %) accounts for the share of parts rejected due to deviations in quality regarding bend angle. The utilisation rate is calculated using the method outlined in [66], as formalised in Equation (7.2).

For the experimental setup, the recorded processing time includes bending operations, dwell periods, and movement between positions. Although the manual nature of this setup makes the utilisation rate somewhat artificial, it is still computed to provide an indicative estimate of production volume within a 24-hour period. This estimation assumes dwell time to be value-adding, despite the laser being inactive during these intervals. Based on this definition, the utilisation rate of the experimental setup is estimated as follows. The values applied in the calculation are based on the throughput time presented in Table 7.2, along with an estimated duration of 7 minutes for mounting and removing the part. This time is classified as non-value-adding, as it does not contribute directly to the processing of the part:

$$\text{Utilisation} = \frac{\text{Tracked Time}}{\text{Time Available}} \cdot 100 = \frac{3848\,\text{s}}{4268\,\text{s}} \cdot 100 = 90.2\% \tag{7.2}$$

To estimate the number of units producible within a 24-hour period, values are drawn from Table 7.2, Equation (7.2), and Appendix C, which provide the throughput time, utilisation rate, and error rate, respectively. Based on these inputs, the estimated number of units producible in a 24-hour period on the experimental setup is:

$$\text{Units} = \left(\frac{86400\,\text{s} \cdot 90.2\%}{3848\,\text{s}}\right) \cdot (1 - 5\%) \approx 20 \;\rightarrow 100\,\text{days} \tag{7.3}$$

Given the results relative to the defined engineering specifications, the current experimental system cannot fulfil an order size of approximately 2,000 units within a reasonable timeframe, as it would take 100 days. To evaluate the scalability and potential of the magnetic levitation laser processing system in addressing this requirement, a production scenario is proposed using a larger configuration comprising 15 tiles and eight movers, as illustrated in Figure 7.3. This estimation is grounded in processing times derived from Table 7.2.

For the scaled scenario, additional elements such as scanning time and a buffer for additional processes are included, while dwell time is deliberately excluded. This is justified by the system's ability to process multiple units in parallel, meaning that dwell time for one unit occurs concurrently with active processing of others, and therefore does not contribute to overall production delay. As a result, only genuinely productive operations, forming, inter-process travel, scanning, and additional processes (extra cooling or corrective forming), are considered in the utilisation calculation as value-adding operations. This approach leverages the routing flexibility of the XPlanar system and provides a more realistic representation of its performance in a production setting. The following values are used in the calculation:

Time Breakdown for Batch Production of 8 Units

No.	Activity	Time [s]	Category
1	Bending (8 × 247 s)*	1,976	Value-adding
2	Travel (8 × 132 s)*	1,056	Value-adding
3	Scanning and additional processes (8 × 130 s)	1,040	Value-adding
4	Removing and remounting	60	Non-value-adding (shared)
5	Transfer between stations	984	Non-value-adding (shared)
	Value-adding time	**4,072**	
	Total time	**5,116**	

Table 7.3: Breakdown of processing and handling times for the batch production of 8 units. *Taken from the experimental setup.

The processing times used in this evaluation are derived from the experimental setup, scaled to accommodate the simultaneous production of eight units. Specifically, the bending and travel durations are identical to those observed during the production of the assessment part on the experimental setup. In a more agile production environment, where fixtures and features vary between parts, these times would naturally differ across product variants.

The scanning and additional processes are estimated as follows: quality control scanning is assumed to take 10 seconds per part, while subsequent processes (such as extra cooling or corrective actions informed by the scanner) are allocated a combined total of 120 seconds for every batch of eight units produced. This allocation also introduces a buffer to account for variability in real-world operation, though these values are only estimates.

Part removal is estimated at 60 seconds per batch, equating to approximately 8 seconds per unit for dismounting and preparing the movers for new parts. Finally, transfer time between stations, when the laser is inactive, is estimated at 984 seconds in total. This value assumes one second per shift and is based on the part's distribution across four feature groups:

Transfer Time Calculation

Group	Passes	Time per Unit [s]	Total Time for 8 Units [s]
Group 1	43	43	344
Group 2	43	43	344
Group 3	21	21	168
Group 4	16	16	128
Total	—	123	**984**

Table 7.4: Transfer time estimation based on number of passes per group.

Using these values, the utilisation rate of the proposed production setup can now be calculated, and inserted into (7.2):

$$\text{Utilisation} = \frac{4072\,\text{s}}{5116\,\text{s}} \cdot 100 = 79.6\% \tag{7.4}$$

To evaluate whether the system can meet an order size of approximately 2,000 units within an acceptable timeframe, the total number of producible units over a 24-hour period is estimated. This requires determining the throughput time per unit and the cycle time associated with the longest bend, bend 1 on Figure 6.7 (70 [mm]), processed at a production speed of 50 [$\frac{mm}{s}$]:

$$\text{Throughput time} = \frac{5116}{8} = 639.5 \text{ s } \rightarrow 10\,\text{min}\,39.5\,\text{s} \tag{7.5}$$

$$\text{Cycle time} = \frac{70 \text{ mm}}{50 \frac{\text{mm}}{\text{s}}} \cdot 43 \text{ passes} = 60.2 \text{ s} \tag{7.6}$$

These values indicate that the scaled-up production system falls short on cycle time and throughput time due to the iterative nature of the process. However, the cycle time criterion would be met if the maximum required bend angle were limited to 15 °. This is primarily due to the elimination of dwell time and the exploitation of the routing flexibility offered by the XPlanar system. The calculated production parameters for the larger setup are subsequently applied in Equation (7.1) to estimate achievable throughput.

$$\text{Units} = \left(\frac{86400\,\text{s} \cdot 79.66\%}{639.5\,\text{s}} \right) \cdot (1 - 5\%) \approx 109 \rightarrow 19\,\text{days} \tag{7.7}$$

Based on the calculated throughput, the proposed system is capable of fulfilling the production order of 2,000 units within approximately 19 days, or 442 hours, under continuous 24/7 operation. This performance satisfies the primary success criteria concerning throughput and product variation. Consequently, further evaluation of the system's performance against the remaining project objectives is warranted.

7.2 Objective 2: Quality and Cost of Poor Quality

Having met the primary success criteria in terms of flexibility and alignment with Industry 4.0 principles, the next objective is to evaluate the quality of parts produced using the magnetic levitation laser-based processing system. This evaluation investigates how the flexibility of the system affects output quality, particularly concerning dimensional accuracy and consistency, while comparing against requirements from conventional manufacturing methods.

To support this evaluation, a model for estimating the Cost of Poor Quality (CoPQ) is implemented. This model provides a quantitative comparison between the proposed system and conventional dedicated solutions by accounting for process-induced defects, rework, and salvation. The assessment focuses on three key quality criteria:

- **Uniformity of Bend Angle:** Evaluation of geometric consistency by analysing the angle profile along the bend (start, midpoint, and end).
- **Tolerance Adherence:** Verification that angular tolerances remain within acceptable limits (e.g. $\pm 1°$) in accordance with industry standards.

- **CoPQ:** Estimation of visible and hidden costs to determine the system's ability to produce repeatable, defect-free components while mitigating the CoPQ.

This objective seeks to determine whether the system can deliver competitive quality performance while maintaining the flexibility advantages established earlier in the study. With the primary criteria defined, the results from producing five assessment parts using the magnetic levitation laser processing system are evaluated with respect to the engineering requirements related to product quality and the influence of the CoPQ, which is revisited in Table 7.5.

Quality

No.	Requirement	Value	Direction	MoSCoW
3.1	*Minimum achievable bend radius*	1 mm	↓	Could
3.2	*Bend angle must be uniform along its length, varying by a set value.*	±1°	↓	Must
3.3	*Tolerance range of current benchmark process*	±1°	↓	Must
3.4	*Maximum permissible defect rate*	5%	↓	Would
3.5	*CoPQ must not exceed an acceptable share of total production cost.*	$\leq$ 15%	↓	Must
3.6	*Should reduce CoPQ compared to conventional methods.*	$\geq$ 20%	↑	Should

Table 7.5: Quality-related requirements and prioritisation.

The experimental results corresponding to these quality-related requirements are presented in Table 7.6:

Experimental Results (Quality and CoPQ Influence)

No.	Parameter	Observed Value
3.1	*Minimum achievable bend radius*	0.35 [mm]
3.2	*Bend angle must be uniform along its length, varying by a set value.**	0.82° / 1.50° / 2.09° / 1.74°
3.3	*Tolerance range of current benchmark process*	+0.67° / -0.49°
3.4	*Observed defect rate*	est. 5%**
3.5	*CoPQ share of total production cost.*	6.13 %
3.6	*Reduction of CoPQ compared to conventional methods.*	28.4%

Table 7.6: Observed experimental results related to quality, compared with the target specifications. *Mean angle uniformity deviation of bends 1 / 8 / 9-14 / 15-20 **Not measured as it is open-loop controlled

The minimum achievable bend radius is measured to be approximately 0.35 [mm]. Although this slightly surpasses the specified engineering requirement, it remains acceptable given the experimental nature of the current setup. The results are also derived using a custom-made arc length detector, indicating that variations may occur between different scans. The uniformity of the bend angle exhibits a maximum deviation of 2.09°, which does not comply with the engineering specification across the start, midpoint, and end of the bend. However, the results indicate that longer bends exhibit slightly greater uniformity, which may be attributed to edge effects, also observed in the variation mapping for smaller bends shown in Figure 6.13. Tolerance adherence is evaluated across the entire part, with the maximum angular tolerance, both under- and overshooting, measured at $+0.67° -0.49°$, within the target specification. This deviation is anticipated due to the use of an open-loop control strategy, where critical parameters such as the number of scan lines, laser power, and scanning speed are defined empirically. While the result is non-conforming, it establishes a relevant benchmark for future implementation of a closed-loop feedback system, which is expected to enhance both uniformity and precision.

The defect rate is estimated at approximately 5%, reflecting the iterative nature of the process and the anticipated implementation of a closed-loop control system. This estimate is further supported by industry stakeholder input, as documented in Appendix C, where a defect rate of 5% was reported. The corresponding CoPQ is the share of the total production cost, and the expected reduction compared to conventional dedicated solutions is evaluated later in this section. These CoPQ estimations are based on a scaled production setup, as detailed in Section 7.3, where a closed-loop control system is assumed to be fully integrated.

CoPQ refers to the total financial losses resulting from non-conforming products or processes within a company. [36] In European manufacturing, CoPQ is estimated to account for 15–25% of total turnover, underlining its significance as a performance indicator. [36] Within sheet metal manufacturing, CoPQ can be broadly categorised into visible and hidden costs. While visible costs, such as scrap and rework, are typically easy to detect and quantify, hidden costs often go unnoticed despite having a more severe long-term impact. These include issues such as warranty claims, administrative overhead, and reputational damage. Poor quality often has a ripple effect, where an issue originating in one area propagates across departments, amplifying its consequences. An overview of the CoPQ structure is illustrated in Figure 7.1.

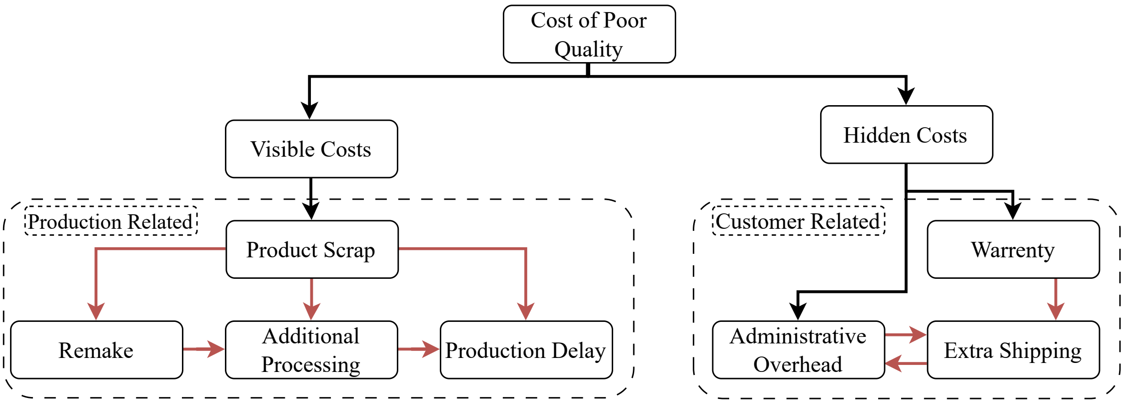


Figure 7.1: Overview of how the CoPQ is divided into visible and hidden costs. Visible costs include scrap, rework, and delays, while hidden costs, such as warranty claims and reputational damage, are less apparent but potentially more severe. Red arrows illustrate the ripple effects of quality failures.

Evaluating the CoPQ is essential for the magnetic levitation laser-based processing system, particularly because the system targets rapid prototyping and low-volume production. In such contexts, even moderate quality-related losses can significantly undermine the system's competitive advantage compared to conventional manufacturing systems. If visible quality costs, such as scrap, rework, or processing delays, become excessive, the trade-off between flexibility and speed is quickly offset. Given the iterative nature of the laser forming process, high process reliability is expected, and CoPQ must be minimised to ensure industrial feasibility.
To assess this, a model is developed to estimate both visible and hidden CoPQ elements within the context of magnetic levitation laser-based processing. While not a full quality assurance study, the model enables an initial quantification of key cost drivers related to poor quality. An overview of the CoPQ framework for the system is illustrated in Figure 7.8.

The CoPQ for the system is determined using the following equation:

$$CoPQ_{Laser} = C_{scrap} + C_{remake} + C_{customer_complaints} - C_{salvage} \tag{7.8}$$

The production cost per unit is estimated at 50.56 DKK, as calculated in Section 7.3, where the material cost is 1.17 DKK per unit. In Equation (7.8), C_{Scrap} denotes the material cost associated with scrapped units, calculated based on the number of defective parts and the quantity of replacement units required. C_{Remake} refers to the production cost of manufacturing both faulty and replacement parts. $C_{CustomerComplaints}$ captures the cost of units rejected by the customer, which may include damages from shipping, insufficient surface quality, or failures during end-use. In contrast, $C_{Salvage}$ represents the recoverable value from under-formed but correctable parts, consid-

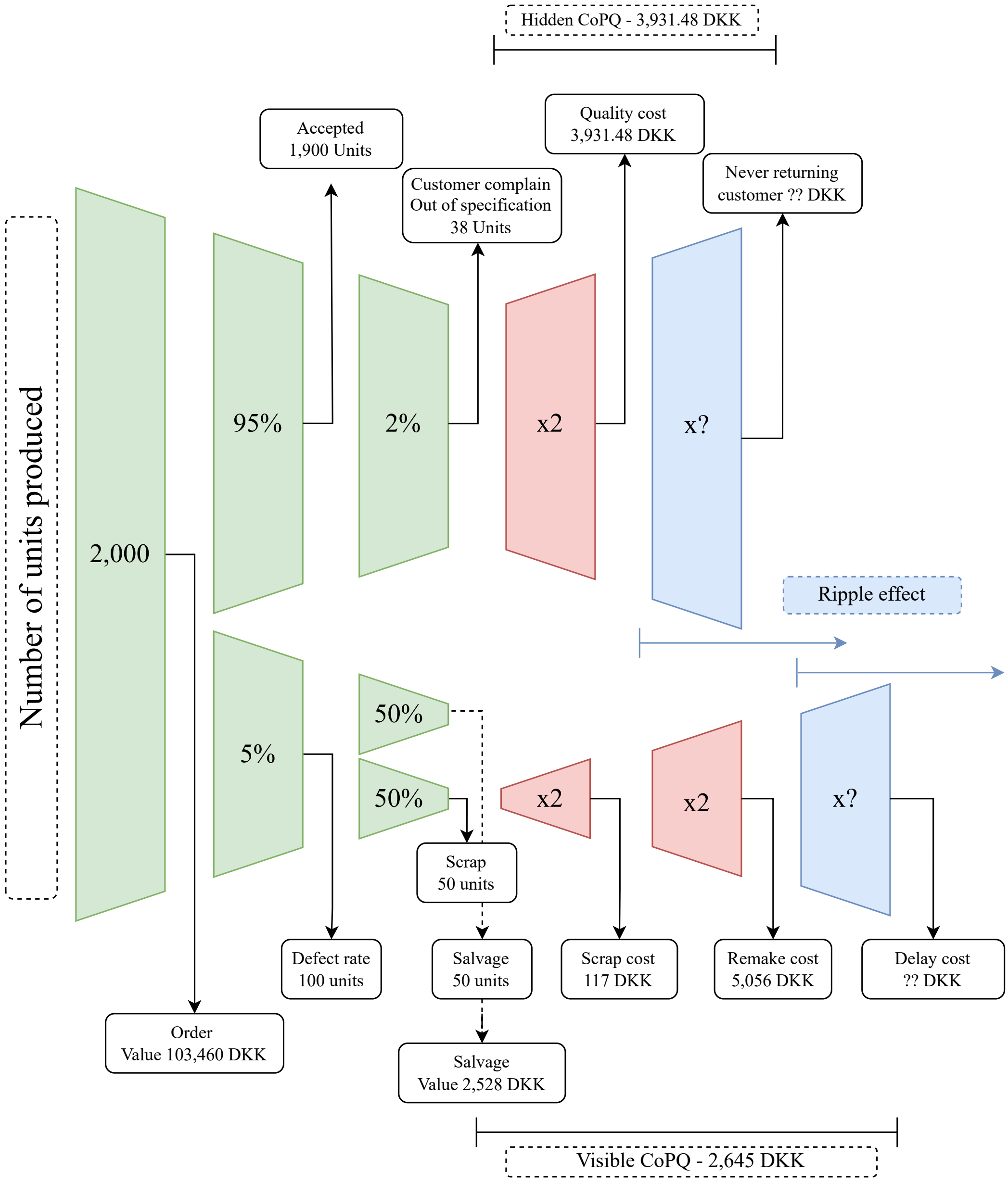


Figure 7.2: Illustration of the CoPQ model for a production batch of 2,000 units, with a total production cost of 103,460 DKK. The model applies a 5% defect rate and categorises the defective units as either salvageable (under-bent, within the possible correction range) or scrap (beyond the acceptable tolerance). It then calculates associated material and remake costs, including the full production cost for replacement units. As indicated by the "×2" on the figure, the model accounts for both the cost of the defective product and the cost of producing its replacement, effectively doubling the relevant production cost per defect. Furthermore, the model illustrates the ripple effect caused by the production. For hidden costs, it considers that the customer may still reject 2% of accepted units due to other deviations, which is based on quality expectations outlined in [67]. Finally, it highlights the reputational impact of undetected quality issues, including the potential loss of returning customers. The production cost of a unit is drawn from the bending-only setup presented in Section 7.3.

ering the associated time and resources for correction. Applying these values, the CoPQ is computed as:

$$\begin{aligned}(50 \cdot 2 \cdot 1.17\,\text{DKK} + 50 \cdot 2 \cdot 50.56\,\text{DKK} + 2,000 \cdot 0.95 \cdot 0.02 \cdot 51.73\,\text{DKK}) - 50 \cdot 50.56\,\text{DKK} \\ = 6,576.48\,\text{DKK} \quad (7.9)\end{aligned}$$

To assess whether the system meets the CoPQ requirement of remaining below 15% of total production costs, the following calculation is performed:

$$\frac{\text{Total CoPQ}}{\text{Total Production Cost}} = \frac{6,576.48, \text{DKK}}{2,000 \cdot 51.73, \text{DKK}} \cdot 100 = 6.3\,\% \quad (7.10)$$

The resulting CoPQ of 6.3% demonstrates that the system satisfies the predefined requirement. This relatively low percentage highlights the potential advantages of laser processing in iterative production, where the process is inherently easier to monitor and control. It is important to note that this result assumes the presence of a closed-loop feedback system within the bending-only production setup which is described in Section 7.3.

The reduction in CoPQ is evaluated based on an industrial interview presented in [34] and in Appendix C, in which a sheet metal manufacturing company reports an estimated 5% defect rate during conventional mechanical forming, where no unit is salvageable. This defect rate is primarily attributed to the springback phenomenon, which causes the final geometry to deviate from the intended shape. To compensate for process deviations, manufacturers typically produce more units than initially required. As reported in [34, 35] and Appendix C, an order of 2000 units commonly results in the production of 2150 units to account for expected defects. Using the CoPQ model in Equation (7.8), excluding salvageable components, this overproduction corresponds to an estimated CoPQ of 8.8% for conventional forming processes. Using this as a benchmark, the reduction achieved by the proposed magnetic levitation laser-based processing system is calculated in Equation (7.11):

$$\frac{8.8\,\% - 6.3\,\%}{8.8\,\%} \cdot 100\,\% = 28.4\,\% \quad (7.11)$$

This result confirms that the system meets the requirement of reducing CoPQ by at least 20%. The significant reduction is attributed to the inherent advantages of laser forming, which eliminates springback due to the fixed plastic deformation that occurs upon cooling. Furthermore, the integration of a closed-loop feedback system enables precise control of the forming process, enhancing repeatability and accuracy, while also adding the possibility of salvaging units.

Beyond quality improvements, this reduction contributes positively to the sustainability of the solution, as there is less scrap compared to conventional dedicated solutions, aligning with key objectives in modern manufacturing practices and the broader goals of the sheet metal sector. [1]

Based on the quality evaluation, the proposed system demonstrates the potential to match or exceed the performance of conventional methods. The first primary criterion of Objective Two is the uniformity of the bend angle, which, based on the results, is found to be outside the specification for smaller bends. Consequently, Objective Three can now be addressed to assess the financial feasibility of adopting the novel laser processing system for rapid prototyping or low-volume, agile production scenarios.

7.3 Objective 3: Cost and Tooling

Having established the flexibility and assessed the potential quality outcome of the experimental system and the proposed system held against their respective requirements, with acceptable results. The final objective is to conduct a cost estimation of the proposed system relative to a dedicated system, thereby highlighting the financial advantages for stakeholders. The cost model developed in this report is based on the hourly cost of running the equipment. This approach is chosen because the system is not designed for mass production, but rather for various small batch productions, where the duration of each batch can vary. The model specifically focuses on direct overhead costs, which include equipment depreciation, labour, and materials. These costs are investigated as key factors influencing the overall cost of the manufacturing processes.
To evaluate the competitiveness of the systems, the model is applied to four different setups: two for the magnetic levitation system, each at different scales, and two for dedicated manufacturing systems, also at varying scales.

Cost and Tooling

No.	Requirement	Value	Direction	MoSCoW
4.1	*Tooling cost (fixation or cutting technique)*	50–80,000 DKK	↓	Must
4.2	*Lead time*	4 weeks	↓	Could
4.3	*Production cost per unit*	100 DKK	↓	Must
4.4	*Total cost of the production system*	≥5% reduction	↑	Must

Table 7.7: Economic requirements: production and tooling considerations.

From the engineering requirements presented in Table 7.7, key cost assessment criteria are defined. If these criteria are fulfilled, the system is considered a viable solution for manufacturing companies engaged in low-volume production or rapid prototyping within the sheet metal industry.

- **Cost pr Unit**: Based on calculations shown in (7.12) and (7.15).
- **Lead time**: Evaluated from start to finish of batch production.
- **Price comparison**: The relative price compared against a dedicated manufacturing system.

Once these criteria are established, cost calculations for the magnetic levitation system are performed. The results are then compared to those of dedicated manufacturing systems and subsequently evaluated against the defined engineering specifications.

7.3.1 Magnetic Levitation Price Estimation

To asses the cost per manufactured unit on the magnetic levitation system two calculations are made, first cost calculation is based on a forming-focused production setup, reflecting the experimental configuration but scaled to accommodate higher production volumes. The second calculation further scales this setup to a level suitable for industrial stakeholders, incorporating all four processes outlined in Chapter 2, making it an "all-in-one" system.

Assumptions

The following assumptions form the basis for the subsequent cost estimations and system evaluations. These parameters reflect standard industry practices, vendor input, and relevant project-specific considerations:

- Skilled labour is estimated at 220 DKK/hour.
- 3d printed fixture and bolts estimate 50 DKK.
- The equipment price is based on inquiry prices from vendors.
- The depreciation period is set to 10 years.
- The salvage value is set to 10 % of purchase prices.
- The batch to be produced is 2,000 units.

The cost per unit is calculated as shown in (7.12).

$$UnitCost = \frac{(Depreciation + Labour) \cdot Hours}{Units} + \frac{Material}{Units} \tag{7.12}$$

Magnetic Levitation: Bend Setup

The smaller-scale production setup is designed primarily for forming operations, with the potential inclusion of finishing. This configuration targets the industry gap identified in the literature study, offering a viable alternative to traditional press brakes. Positioning laser forming on the magnetic levitation system as a practical and competitive solution for industrial applications. Such a setup is illustrated in Figure 7.3, consisting of 15 tiles, 8 movers with accompanying equipment, and a 500 [W] laser sufficient for performing these low-power operations, forming and finishing.

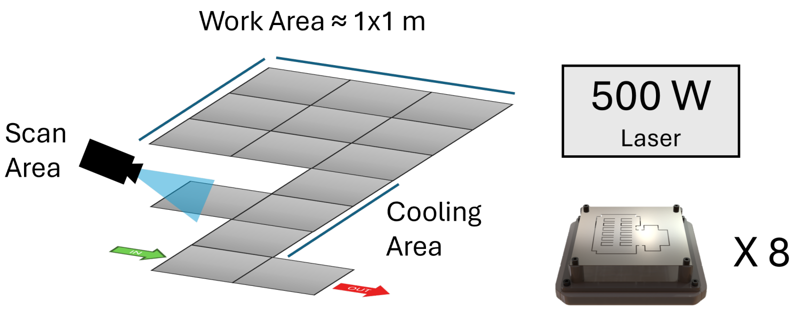


Figure 7.3: Small scale setup, layout consisting of 15 tiles and one work area of $\approx 1m^2$ dedicated to low-power tasks such as finishing and forming.

To evaluate the economic feasibility of the magnetic levitation system, a cost analysis is conducted for the small-scale setup illustrated in Figure 7.3. The total system price is estimated at 853,561.66 DKK, as outlined in Appendix D. Assuming a 10-year depreciation period and continuous operation of 8,760 hours annually, this results in a yearly depreciation of 76,820.55 DKK, equivalent to 8.77 DKK per operational hour. From Section 7.1, the production time required for a batch of 2,000 units is acquired and inserted in (7.13).

$$51.73, \text{DKK} = \frac{(8.77\,\text{DKK} + 220\,\text{DKK}) \cdot 442[h]}{2,000} + \frac{2,347.38\,\text{DKK}}{2,000} \tag{7.13}$$

For the smaller-scale magnetic levitation production setup dedicated to forming sheet metal parts, the cost per unit, including material costs, is estimated at 51.73 DKK. This is later compared to a dedicated manufacturing setup operating at a similar production scale to evaluate if the system is a viable option.

Magnetic Levitation: Large Scale Setup

The larger-scale production setup is capable of performing all four manufacturing processes, thereby functioning as an integrated "all-in-one" system, designed to meet the demands of the industry. Such a setup is illustrated in Figure 7.4, consisting of 36 tiles, 25 movers with accompanying equipment, and two laser sources of 500 and 1000 $[W]$. Two laser sources are chosen for dedicated low-power tasks, such as finishing and forming and high-power tasks, such as welding and cutting.'

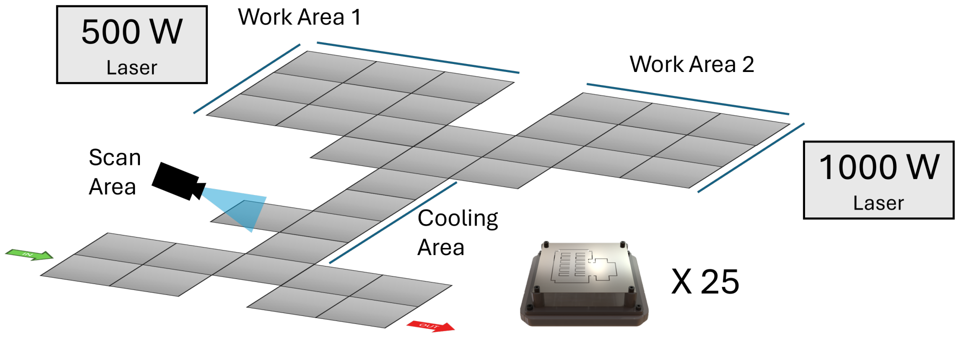


Figure 7.4: Large scale setup, layout consisting of 36 tiles and two work areas of $\approx 1m^2$. Work area 1 is dedicated to low-power tasks such as finishing and forming and work area 2 for high-power tasks such as welding and cutting.

To assess the scalability and cost implications of the proposed system, a cost analysis is performed for the large-scale magnetic levitation setup, shown in Figure 7.4. The total system cost is estimated at 1,924,999.70 DKK, as documented in Appendix D. Based on a 10-year depreciation period and 8,760 annual operating hours, the yearly depreciation amounts to 173,249.97 DKK, equivalent to 19.78 DKK per hour. The large-scale setup includes two independent work areas, allowing simultaneous processing of two parts, thereby halving the required production hours per unit.

$$27.66, \text{DKK} = \frac{(19.78\,\text{DKK} + 220\,\text{DKK}) \cdot 221[h]}{2,000} + \frac{2,347.38\,\text{DKK}}{2,000} \tag{7.14}$$

For the larger-scale production setup capable of performing cutting, forming, welding, and finishing operations, the cost per unit, including material costs, is estimated at 27.66 DKK. This is subsequently compared to a dedicated manufacturing setup operating at a similar production scale, to see if an "all-in-one" solution is competitive with a combination of separate dedicated manufacturing systems.

7.3.2 Dedicated System Price Estimation

The cost estimation for the dedicated manufacturing setup is carried out in two stages, following the earlier calculation for the magnetic levitation system. The first stage considers a setup limited to bending operations, while the second includes a full-scale configuration encompassing all four manufacturing processes: cutting, forming, welding, and finishing, as defined in the literature study in Chapter 2.

Assumptions

The following assumptions apply to the cost estimation of the dedicated manufacturing systems. As this is the second set of assumptions presented, the values here are tailored to reflect conventional equipment and production practices, based on vendor data, literature sources, and relevant industry standards:

- Skilled labour is estimated at 220 DKK/hour.
- Tooling price for special press brake dies and punches is $\approx 70,000$ DKK. [68] Tools for other equipment is included in purchase of the equipment.
- The equipment price is based on minimum prices used in the literature study, see Appendix A
- The depreciation period is set to 10 years.
- The salvage value is set to 20 % of the purchase price.
- Utilisation rate is set to 75%. [66]
- The batch to be produced is 2,000 units.

The cost per unit is calculated as shown in (7.15).

$$UnitCost = \frac{(Depreciation + Labour) \cdot Hours}{Units} + \frac{Material}{Units} + \frac{Tool\ Depreciation}{Units} \tag{7.15}$$

Dedicated: Bend Setup

This setup represents the direct industrial counterpart to the smaller-scale bending-only configuration of the magnetic levitation system. As illustrated in Figure 7.5, the system comprises a conventional press brake integrated with a robot unit to enable automated part handling. This configuration reflects a solution within the industry for automated sheet metal forming and serves as the benchmark for evaluating the performance, cost, and flexibility of the proposed magnetic levitation-based approach.

Figure 7.5: Press brake and robot needed for an automated conventional forming only setup.

To provide a basis for economic comparison, a cost evaluation is carried out for the dedicated small-scale setup shown in Figure 7.5. The total system cost is estimated at 953,105.64 DKK, as detailed in Appendix D. Assuming a 10-year depreciation period and 8,760 operating hours per year, the annual depreciation amounts to 76,248.45 DKK, corresponding to 8.70 DKK per hour. In addition, a tooling cost of 71,087.90 DKK must be depreciated over the production of each batch, further contributing to the unit cost.

According to [69], a press brake can produce small, rather complex parts at a rate of 400 cycles (bends) per hour. The assessment part requires 20 bends, meaning that 20 parts can be produced per hour under ideal conditions. However, factoring in the utilisation rate of 75%, the actual output is reduced to 15 parts per hour. [66] Consequently, the total production time for 2,000 parts on a dedicated manufacturing system is estimated to be 133.3 hours.

$$51.96\,\text{DKK} = \frac{(8.70\,\text{DKK} + 220\,\text{DKK}) \cdot 133.3[h]}{2,000} + \frac{2,347.38\,\text{DKK}}{2,000} + \frac{71,087.90\,\text{DKK}}{2,000} \tag{7.16}$$

For the small-scale dedicated production setup capable of performing bending only, the cost per unit, including material costs, is estimated at 51.96 DKK. Compared against the magnetic levitation setup of the same scale, the price difference is negligible; this suggests that the batch size is close to the break-even point regarding cost per unit at this scale. Although the production time is more than three times as fast as that of the comparable magnetic levitation system, this advantage may be diminished when considering the lead time for specialised press brake tools, which typically ranges from 3 to 4 weeks.

Dedicated: Large Scale Setup

A complete setup incorporating four manufacturing operations, comparable to the larger-scale magnetic levitation system. For such a setup, four different machines are needed; four systems are picked from the Literature study in Chapter 2. Figure 7.6 shows the systems and robots required for automation.

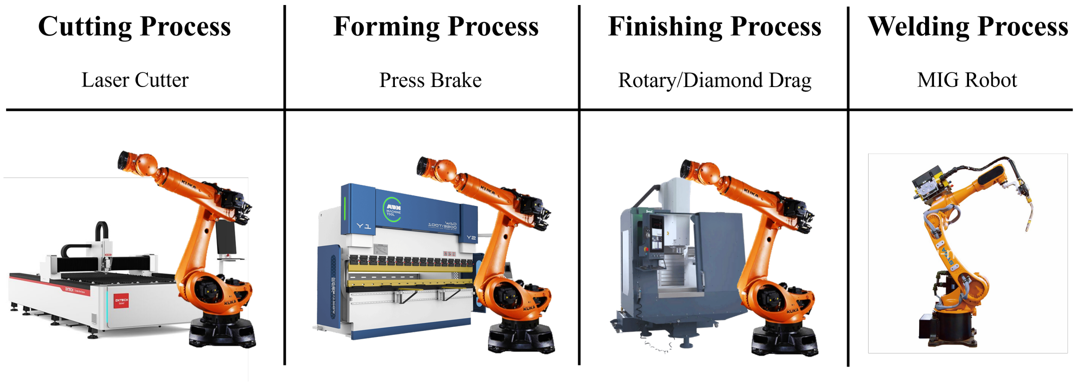


Figure 7.6: Systems and equipment needed for an automated large-scale conventional setup.

To complete the economic benchmark, a cost assessment is conducted for the dedicated large-scale setup illustrated in Figure 7.6. The total investment is estimated at 3,289,416.24 DKK, as presented in Appendix D. With a 10-year depreciation period and 8,760 operational hours annually, the yearly depreciation amounts to 263,153.30 DKK, corresponding to 30.04 DKK per hour. Additionally, a tooling cost of 71,087.90 DKK must be depreciated across the production of the batch, further increasing the total unit cost.

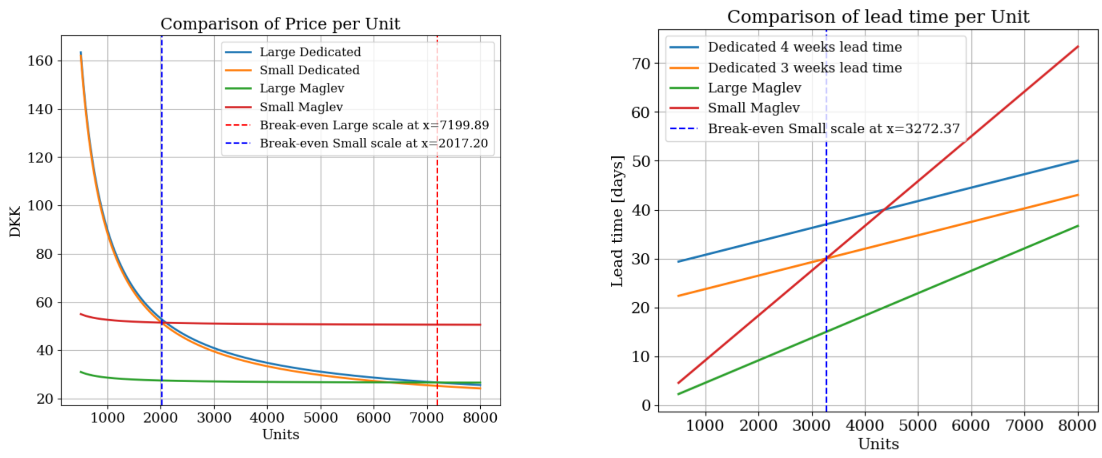
The production hours required are set to the same value as the bend-only setup, meaning that the press brake is assumed to be the bottleneck. This is based on the part being complex for a traditional press brake to produce, meaning that the cutting, eventual welding and finishing operations are significantly faster compared to the forming.

$$53.38\,\text{DKK} = \frac{(30.04\,\text{DKK} + 220\,\text{DKK}) \cdot 133.3[h]}{2,000} + \frac{2,347.38\,\text{DKK}}{2,000} + \frac{71,087.90\,\text{DKK}}{2,000} \tag{7.17}$$

For the large-scale dedicated production setup capable of performing all four manufacturing operations, the cost per unit, including material costs, is estimated at 53.38 DKK. Compared against the magnetic levitation setup of the same scale, the price almost doubled, this is due to the high cost of automating the process, as four robots are needed. For the full-scale setup, even though the assessment part does not involve all four systems, the additional price is only a fraction compared to the small-scale dedicated system.

7.3.3 Summery

In summary, when comparing the setups regarding cost per unit and achievable lead time as shown in Figure 7.7. The magnetic levitation system clearly shows characteristics of the volume flexibility that is strived for in low volume production, as the cost per unit is constant from 1,000 manufactured units and beyond, as seen in Figure 7.7a. Furthermore, the assessed batch size of 2,000 lies just within the break-even point of the smaller scale systems, while the large scale systems break-even at 7,200 units. This suggests that the system is well suited for low production volumes between 1 and 10,000 units. Comparing the lead time per unit shown in Figure 7.7b, it can be seen that the small-scale magnetic levitation system is faster than the dedicated system until a batch size of approximately 3,200 units and 15,000 units for the large-scale systems, approving medium volume production (10,000-50,000 units), when factoring in a 3 week lead time of specialised tools.



(a) Comparing the price per unit.

(b) Comparing the lead time per unit.

Figure 7.7: Volume flexibility assessment regarding cost and lead time.

Comparing the magnetic levitation systems against the specified requirements regarding cost, all can be deemed fulfilled, comparing Table 7.8 and 7.7.

Cost and Tooling

No.	Requirement	MS Result	ML Result
4.1	*Tooling cost (fixation or cutting technique)*	400 DKK	1,250 DKK
4.2	*Lead time*	19 days	10 days
4.3	*Production cost per unit*	51.73 DKK	27.66 DKK
4.4	*Total cost of the production system**	11.66%	70.88%

Table 7.8: Economic requirements and corresponding results for both magnetic levitation systems. MS: small-scale, ML: large-scale. *Reduction in price compared to a dedicated manufacturing system.

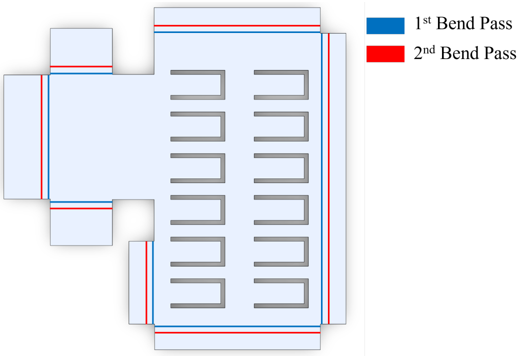
8. Discussion

The discussion begins by outlining the manufacturing process and summarising the key results obtained from the experimental setup. These results then form the basis for individual discussions structured around the three main objectives: flexibility, quality, and cost. Each objective is assessed in relation to the success criteria defined in Chapter 4, evaluating the extent to which the system meets the intended performance targets. The chapter concludes with an overall assessment of the magnetic levitation laser-based production system, considering its alignment with the broader engineering requirements and its potential industrial applicability.

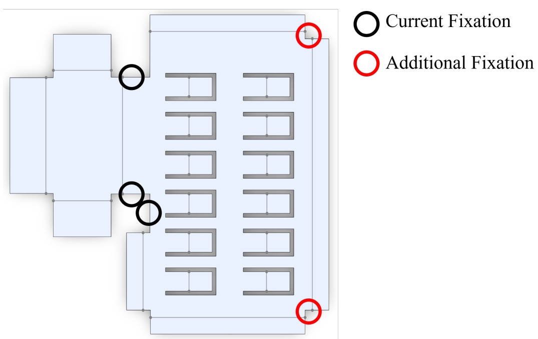
8.1 Manufacturing Strategy and Measurement Method

This section discusses the open-loop manufacturing strategy for the assessment part, with a focus on process control, observed deviations, and dimensional evaluation using 3D scanning.
The part is produced using an empirically adjusted open-loop approach, making the system vulnerable to manufacturing errors, particularly in angle accuracy. Iterative modifications are made between part iterations based on visual and measured defects. As highlighted in Section 6.4.3, bend sequencing plays a critical role in mitigating heat accumulation and warping. Although adding external cooling and increasing dwell time helps reduce thermal effects, noticeable warping persists. This is addressed by strategically grouping bends to first stiffen the inner regions of the part, followed by outer bends, and finally returning to the initial scan line, as illustrated in Figure 8.1a. These findings provide a valuable foundation for the future implementation of a closed-loop feedback control system, as they help identify where warping is most likely to initiate or be prevented.

Furthermore, approach two, selected in Section 6.2.3, introduces flexibility through a cutout template and using fixation points to the outer plate. While this setup enhances adaptability, the use of only three fixation points could lead to slight warping along longer unsupported edges. Figure 8.1b highlights the current fixation layout and where fixation points can be added. Based on this, it is worth experimenting whether adding one or two fixation points near overhangs could help mitigate warping.



(a) Illustration of the applied bend sequence strategy. Bends are grouped to stiffen the inner regions of the part first (blue), followed by outer bends (red), then incremental passes towards the initial scan line (blue). This sequencing approach mitigates thermal distortion and warping during processing.



(b) Visualisation of fixation points applied in approach two. The use of only three fixation points enables flexibility through a cutout template (black), but results in warping along longer unsupported edges. Additional fixation points near overhangs may help reduce deformation (red).

Figure 8.1: Key design considerations influencing part stability during manufacturing. (a) Bend sequencing to control heat accumulation and warping. (b) Fixation layout affecting structural support and deformation during processing.

During the manufacturing of the five assessment parts, a fluctuation of approximately ± 5 $[W]$ in laser power is observed, both between different bends and along longer bends. This variation is attributed to the use of a 3 $[kW]$ laser system, which operates with reduced stability at low power levels, combined with a worn control module. These inconsistencies likely contribute to non-uniform bend angles along the length of the part. This is consistent over all bends for a part, and is due to the temperature rise in the laser modules, and is noticed to differentiate between different parts.
Angle measurement is performed using 3D scanning to generate point clouds, from which bend angles, radii, and arc lengths are extracted. This method is selected for its potential integration into a closed-loop feedback control system. Point cloud data can be updated during processing, enabling real-time identification of bending planes and deviations. Moreover, this technique supports quality control by allowing direct comparison between the scanned part and the original CAD model, thereby verifying compliance with specified tolerances. The method could also be used to assign CAD files to dedicated movers, enhancing mix and routing flexibility.

8.1.1 Objective 1: Flexibility and Industry KPIs

The discussion for objective 1, flexibility and industry KPIs, focuses on the chosen manufacturing approach, as it primarily determines the system's flexibility. While parameters such as achievable order size and standard product envelope are relevant, the discussion centres on the system's ability to produce different product features.

The results demonstrate that the selected approach supports the four required product features and has the potential to handle additional geometries. However, extending this flexibility would require manual or robotic part repositioning, such as for achieving a directional shift bend seen in Figure 6.2, which falls outside the scope of this project. This should be tested and see whether it is achievable or this induces new implications. Approach one, which involves a more complex and adaptive fixture with moving elements, could potentially offer greater product flexibility than the current cutout template used in approach two. Its reconfigurability could enable support for a wider range of geometries, as it could turn the product and add more flexibility to the limited axes of the XPlanar system, specifically rotation around X and Y axes stated in Table 2.3. However, this comes at the cost of increased production time, as repositioning, securing, and adjusting the part would be required for each scan line, and therefore each bend. Although such operations could theoretically be carried out during dwell time, the complexity of implementation and the resulting uncertainty in tolerance control pose significant quality challenges for industrial applications. Which would be a trade-off that the manufacturing company should evaluate if it decides to invest in the magnetic levitation system.

8.1.2 Objective 2: Quality and Cost of Poor Quality

The discussion for objective 2 highlights the limitations of the experimental setup, which operates under an open-loop control system. As previously mentioned, this method leaves the system vulnerable to manufacturing errors, which is reflected in the results. Although the tolerances for bending angles are met, the uniformity of the bend angles does not consistently align with the defined engineering specifications. These deviations may be caused by the phenomenon called edge effect, which can be seen especially for the bends with short scan passes. This variation points to the potential advantages of incorporating a closed-loop feedback control system, which could enhance process accuracy and consistency. By doing so, it would reduce deviations such as over- or underforming, bringing results even closer to the engineering specifications. Consequently, the parts may only require one or two additional passes through the production system, adding minimal to no extra production time.

Furthermore, the system demonstrates advantages when comparing the share of CoPQ with that of conventional systems. In particular, the iterative nature of laser processing enables the recovery of under-formed parts that fall just outside specification limits. This capability supports a more sustainable production method by reducing scrap and material waste. When evaluated in terms of material waste before, during, and after production, the system aligns with principles of green manufacturing. As introduced in Chapter 1, reducing waste and improving resource efficiency are critical objectives for modern industry, and the results suggest that the proposed system contributes positively to these goals.

8.1.3 Objective 3: Cost and Tooling

The cost calculated for the third objective represents a conservative estimate of the unit cost, since it only covers direct overhead. The true price per unit will be higher once indirect costs, such as R&D engineering and system servicing, are included. This might be higher for the magnetic levitation system compared to the dedicated system due to its complexity, as feedback control is rooted in the system.
An evident advantage of the magnetic levitation-based system is the significant reduction of lead time typically associated with conventional manufacturing methods. As no physical tooling or setup changes are required between product variants, the system enables immediate production once digital instructions are received. This rapid responsiveness presents a strong incentive for industry stakeholders, particularly in sectors where short delivery times, mass customisation, or frequent design iterations are critical. Although the long lead time for the dedicated system could be reduced if planned, by ordering new tools for upcoming batches while producing the current batch, as shown in Figure 8.2.

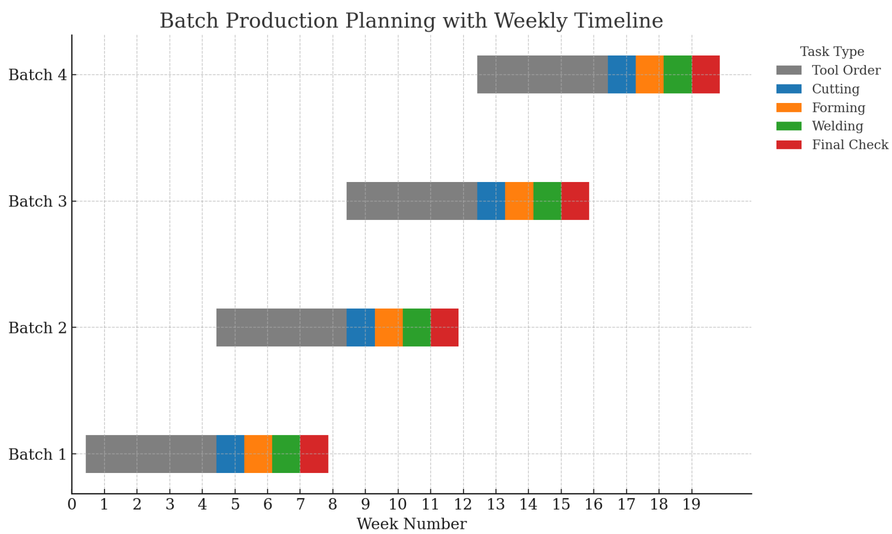


Figure 8.2: Example of optimal production planning by ordering tools in advance.

Following this planning approach, the dedicated system will outcompete the magnetic levitation system on batch sizes greater than approximately 10,000 units rather than 15,000 units, limiting the magnetic levitation system to low volume production. Scaling the magnetic levitation system is observed to reduce the price per unit mainly due to the increased production speed caused by scaling and the advantage of not having to invest in specialised tools, except relatively cheap 3D printable fixtures. This inherent feature makes the magnetic levitation system favourable, as it can be tailored for each customer at negligible expense and can hold multiple configurations for each customer. Dedicated systems typically incur additional costs associated with the design and production of tailor-made fixtures, an issue previously identified as a key bottleneck in conventional manufacturing setups.

8.2 TRL Assessment of Magnetic Levitation Laser-Based Production System

The prioritisation of objectives aligns with the Technology Readiness Level (TRL) framework, a commonly used scale for evaluating the maturity of emerging technologies. As shown in Figure 8.3, the TRL provides a standardised method for assessing technological development, from initial concept validation to full industrial implementation.

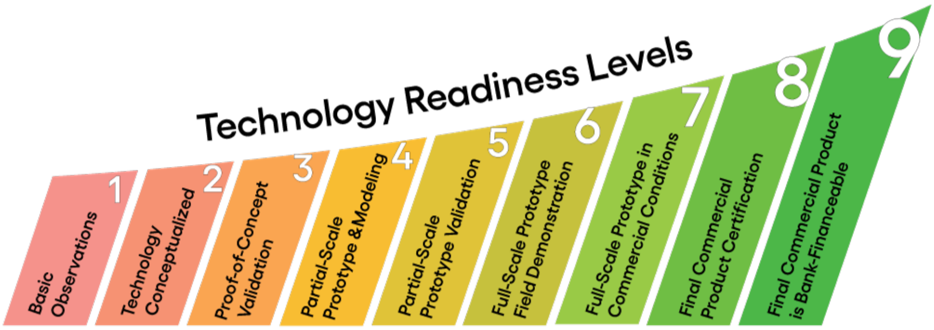


Figure 8.3: Technology Readiness Level adapted from. [70]

Levels 1-3 are already established before working on this thesis, as basic research and proof-of-concept are demonstrated regarding laser forming and magnetic levitating work tables are well-researched. [9] The first objective then covers TRL 4-5 by incorporating the two technologies into a partial-scale experimental setup, and validating what is possible on the experimental system. The second objective defines the importance of why control feedback should be implemented to meet industry standards, thereby reaching TRL 6. Finally, the third objective aims to demonstrate the financial benefits and considerations of implementing the magnetic levitation laser processing system by developing a mockup model of a full-scale system and assessing the cost as per the requirement of reaching TRL 7.

9. Conclusion

This thesis builds upon earlier work as introduced in Chapter 1, and explores design changes at the component level for making an evaluation of magnetic levitation for laser-based sheet metal forming. The aim is to investigate and assess whether the system can address the gap found in the literature study Section 2.1 within the industry of increasing flexibility for low-volume and rapid prototyping productions. Three objectives are defined for assessing magnetic levitation in an industrial setting, which are flexibility, quality and cost. The two-stage literature study reveals that while laser technologies are well established for cutting, welding and finishing, laser forming remains underutilised in industry. Simultaneously, there is a growing demand for flexible, tool-less systems that can support mass customisation and reduce lead times. Furthermore, existing robotic and galvo-based systems often struggle to combine high product flexibility with high processing speed and consistent quality in small batch contexts. Leading to the research objective:

How can component-level design and strategic approach of the magnetic levitation laser process system improve flexibility, quality, and cost in industrial applications?

The proposed developed system in this thesis is based on a planar magnetic levitation platform in combination with a laser. Two fixation approaches are proposed to accommodate product flexibility and improve the general flexibility at the component level. Approach two, using a cutout template, is selected through a systematic decision matrix, due to its simplicity, lower fixture complexity, and ability to support iterative processing.

Objective 1: Flexibility and Industrial KPIs

This objective evaluates whether the system can compete with a conventional dedicated system regarding industry KPI, and sees if the flexibility influences these KPIs. The objective is met through the successful production of four distinct product features, validated through the manufacturing of an assessment part. This is achieved using approach two, which enables the system to handle multiple feature types without reconfiguration or external manipulation, thus supporting the product flexibility within a low-volume production. The experimental setup does not meet the defined targets for cycle time, throughput time, or production volume, primarily due to its limited configuration and the iterative nature of the laser forming process. However, when scaled, the system demonstrates the potential to achieve production volumes of approximately 2,000 units, consistent with typical batch sizes for specialised or custom components in the sheet metal industry. Although the scaled configuration does not fully satisfy the time-efficiency requirements, the overall processing time remains within an acceptable margin. This, combined with the system's significantly reduced lead time, positions it as a competitive alternative to conventional dedicated manufacturing systems.

Objective 2: Quality and Cost of Poor Quality

In terms of quality, the results show that while the tolerance of bend angles is achieved, meeting industrial standards, the system does not demonstrate consistent uniformity across the bend angles. This suggests that there is significant potential for improvement through the integration of a closed-loop control system. Such a system, potentially based on real-time 3D scanning and point cloud comparison with CAD models, could help address the lack of uniformity and further reduce variation, improving overall consistency. Furthermore, the ability to iteratively adjust or reprocess under-formed parts introduces a level of resilience not found in conventional systems. This feature contributes directly to a reduced CoPQ of 28.4% compared to conventional manufacturing systems, as fewer parts are scrapped and more can be salvaged, supporting both economic and environmental objectives.

Objective 3: Cost and Tooling

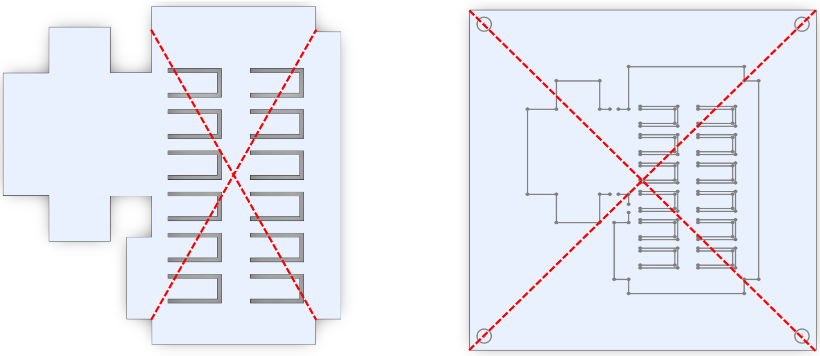
From a cost perspective, the system presents a compelling case for low-volume applications. The unit cost remains constant regardless of batch size, 51,73 DKK and 27,66 DKK for the small and large scale systems, respectively, as no dedicated tooling or costly reconfiguration is required. This eliminates high upfront tooling costs associated with conventional systems. Although the scalability of the experimental setup is limited by hardware constraints and physical workspace, the modular nature of the system makes it adaptable to different product sizes and configurations. The cost model supports the conclusion that the system is financially viable for rapid prototyping, custom orders, and low-volume production, particularly when flexibility and short lead times are prioritised.
Overall, the results demonstrate that magnetic levitation in laser processing for sheet metals fulfils its intended objectives within the defined scope of the thesis. The system holds clear industrial relevance by offering a flexible, sustainable, and economically viable alternative to conventional production methods. It represents a promising step toward an integrated "all-in-one" laser processing platform capable of supporting multiple processes, cutting, forming, welding and finishing.

10. Further Works

This section outlines future directions to improve system performance and industrial use. A cross pattern may reduce warping by increasing stiffness. Integrating a closed-loop system using 3D scanning could improve accuracy through real-time correction. Scaling to multiple movers requires motion mapping and structured sequencing. These improvements aim to enhance flexibility, precision, and readiness for low-volume production.

10.1 Manufacturing Improvement Ideas

During the manufacturing of the assessment part, noticeable warping occurred as a result of thermal stresses induced during laser forming. While this was partially mitigated through improved bend sequencing, specifically by stiffening the part via initially processing the inner scan lines, as illustrated in Figure 8.1a. Further improvements are needed to enhance dimensional stability and consistency. One proposed concept involves introducing structural stiffening by pre-forming a cross pattern on the larger flange area of the part prior to laser forming or as a part of the laser forming process. This could be implemented either before the part is cut or as an early forming step in the process, the location of the cross patterns can be seen in Figure 10.1.



(a) A small cross pattern introduced on the larger flange surface to increase rigidity through local deformation.

(b) A larger cross pattern covering more surface area to provide broader structural reinforcement.

Figure 10.1: Proposed structural stiffening concepts to counteract warping. Both concepts aim to induce upward curvatures that compensate for thermal deformation during laser forming.

The underlying hypothesis is that introducing stiffening features may generate opposing curvatures that mitigate thermal warping during laser processing. If effective, this strategy could enhance the flatness of the final part without compromising system flexibility or processing time, thereby presenting a promising avenue for future research and experimental validation. However, this approach may also introduce additional process instability, as the effectiveness of the stiffening patterns could vary depending on the grain structure of the sheet metal. This highlights the significant impact that minor variations can have on the overall quality of the final component.

10.2 Closed-Loop Control System

As highlighted in the quality-related results, the current system operates without feedback and therefore provides limited process control. To improve consistency and accuracy, future work should focus on implementing a closed-loop control system for laser forming. The control strategy can be developed using a 3D scanner, which generates a point cloud of the formed part, and then generates planes to calculate the angle. By comparing the measured bend angles to the CAD model, deviations can be identified in real time. Based on this comparison, corrective actions, such as adjusting laser power to bend further, repeating a bend, or rejecting the part, can be issued automatically. This would also reduce the reliance on empirically determined process parameters, as the feedback system could learn the deformation per scan over time, potentially using machine learning or AI-powered algorithms, thereby further decreasing the system's lead time. Such an approach would enhance process reliability and reduce deviations in formed geometry. A similar feedback mechanism has been demonstrated by Nikolov et al. [4], where a closed-loop system adjusts over iterations to control deformation. This is visualised in Figure 10.2, which shows the S-curve response used to guide power control in relation to the desired bend angle.

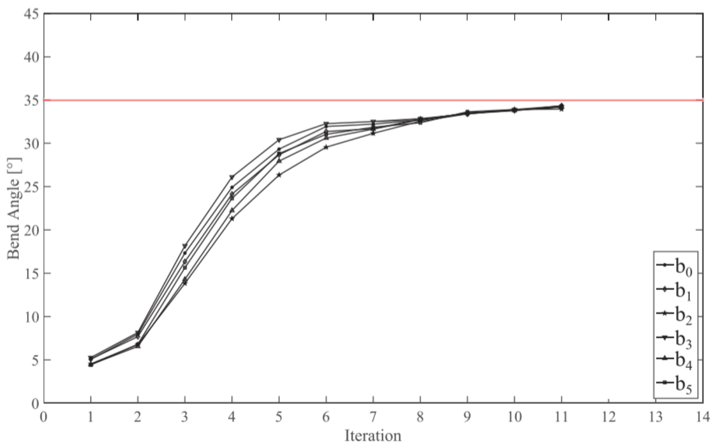
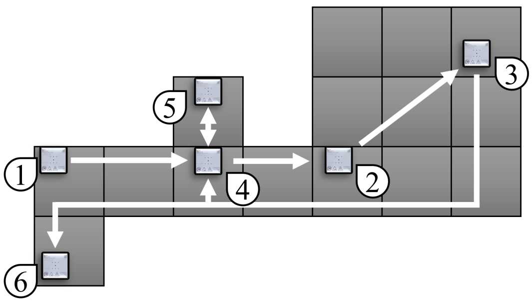


Figure 10.2: Graph adapted from [4] showing closed-loop control of laser forming, based on iteration feedback.

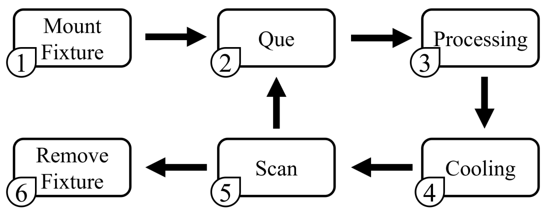
Introducing a closed-loop system would significantly increase the quality and repeatability of the laser forming process, thereby strengthening the system's industrial potential. With improved accuracy, stakeholder interest is likely to grow, leaving cost and scalability as the main remaining considerations, addressed in the following sections.

10.3 Scaled Up Production

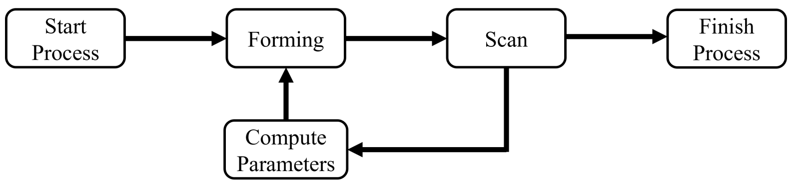
To truly test the proposed system's performance and determine whether objectives two and three are fulfilled, regarding achievable quality, CoPQ and cost per unit, it should be tested on a relevant scale. To assess this, a test of the smaller-scale magnetic levitation system is proposed with incorporated quality control in the form of a closed-loop system, shown in Figure 10.3c. The routing and position of the different stations are illustrated in Figure 10.3a and 10.3b.



(a) Small-scale magnetic levitation system illustrating routing between positions.



(b) Explanation of positions.



(c) Proposed closed-loop design of forming process, new parameters are calculated between each iteration of scan lines.

Figure 10.3: Design of the proposed test on an up-scaled production layout.

Testing this system will also provide insight into whether the system can achieve the same performance as a dedicated system if the products produced only consist of simple features, e.g a single 90-degree bend. If the system successfully demonstrates its ability to perform this task, it would be relevant to explore the potential of scaling up to a larger, integrated, all-in-one system. The rationale is that if the system can already be used for individual operations such as forming or engraving, it could serve as a modular foundation. A scaled-up version would allow for production expansion by enabling the same system to operate as a dedicated forming unit or as part of a more comprehensive laser processing platform. This modular scalability could enhance production flexibility while reducing the need for multiple specialised systems. Furthermore, in this test on the smaller-scale system, the cost estimation can be performed in-depth, more than the conservative estimation in Section 7.3.

Regarding volume flexibility, the current order size estimation is based on a theoretical setup capable of producing eight parts in the time the experimental system produces one. To validate this, future work should aim to realise the theoretical setup and test its feasibility in practice. This includes examining whether the routing flexibility enables effective operation in a low-agility production context. A relevant benchmark could involve processing eight different product variants simultaneously on eight movers to assess the system's responsiveness and adaptability. Finally, to evaluate volume flexibility under realistic conditions, the system should be tested with actual product variants from a sheet metal manufacturing company. This would allow comparison between the number of units produced within the lead time typically required for conventional tooling. These three types of flexibility, product, routing, and volume, should be assessed in future iterations to confirm the system's suitability for both mass customisation in low-volume batch production and rapid prototyping scenarios. The results so far indicate that the magnetic levitation-based system can be competitive and holds significant promise in these domains.

Bibliography

Literature

[1] *Sheet Metal Market Size, Share And Growth Report, 2030*. Tech. rep. Grand View Research, 2023.

[2] *Sheet Metal Market Size & Share, Industry Trends Report 2032*. Tech. rep. SNS Insider, May 2022.

[3] *Sheet Metal Market Size & Share, Global Forecast Report 2037*. Tech. rep. Research Nester, Oct. 2024.

[4] G. N. Nikolov et al. "Computer-aided process planning system for laser forming: from CAD to part". In: *International Journal of Production Research* 62.10 (May 2024), pp. 3526–3543.

[5] Serope. Kalpakjian, Steven R.. Schmid, and K. S. Vijay. Sekar. *Manufacturing engineering and technology*. Pearson Education Limited, 2023, p. 1312.

[6] William M. Steen and Jyotirmoy Mazumder. *Laser Material Processing*. 4th ed. Springer-Verlag London Limited, 2010, pp. 1–558.

[7] Georgi Nikolaev Nikolov, Anders Noel Thomsen, and Morten Kristiansen. "Hardening in laser forming under the temperature gradient mechanism". In: *IOP Conference Series: Materials Science and Engineering* 1135.1 (Nov. 2021), p. 012006.

[8] T. B. Lauwers, Z. K. Edmondson, and R. L. Hollis. "Free-roaming planar motors: Toward autonomous precision planar mobile robots". In: 5 (Apr. 2004), pp. 1–6.

[9] Mads Holm Andersen and Mads Augustinus Frøhlich. *Title: Design and Development of a Reconfig-urable Manufacturing System for Laser Processing of Customisable Name Tags Using a Novel Workpiece Manipulation Strategy*. Tech. rep. Aalborg University, 2024.

[10] Deepthi G. "Sheet Metal Manufacturing: Innovating Industrial Techniques". In: (Aug. 2024).

[11] Lilly Lilly. "EDM vs Laser vs Waterjet vs Plasma: Which CNC Cutting Is a Good Fit?" In: ().

[12] Kat de Naoum. "All About Sheet Metal Forming | Xometry". In: (Dec. 2023).

[13] Tomasz Trzepieciński. "Recent Developments and Trends in Sheet Metal Forming". In: 10.6 (June 2020), p. 779.

[14] Rob Goldiez. "15 Types of Welding Processes with Their Advantages and Limitations". In: (May 2024).

[15] Shane. "7 Types of Robotic Welding and Their Uses - MFG Shop". In: (Dec. 2024).

[16] Greg Paulsen. "How Does Metal Engraving Work?" In: (Feb. 2022).

[17] Stevenson J.William. *Operations Management*. McGraw-Hill Education, 2015, pp. 236–259.

[18] Slack Nigel, Brandon-Jones Alistair, and Johnston Robert. *Operations Management*. Pearson Education Limited, 2016. ISBN: 9781292098715.

[19] Ningjian Huang and Robert Inman. "Product quality and plant build complexity". In: 48.11 (May 2010), pp. 3105–3128.

[20] Elena. "Robot Laser Application in Manufacturing". In: (Nov. 2023).

[21] Emmanuel Afrane Gyasi et al. "Prospects of Robot Laser Cutting in the Era of Industry 4.0". In: 10 (Aug. 2022), pp. 639–655.

[22] J. R. Lawrence, ed. *Advances in Laser Materials Processing: Technology, Research and Applications*. Elsevier Ltd., 2018, pp. 224–227.

[23] Alessandro Ascari et al. "High speed laser cutting of ultrathin metal foils for battery cell production". In: 35 (2023).

[24] Kai Wu and Bernd Kuhlenkoetter. "Dynamic behavior and path accuracy of an industrial robot with a CNC controller". In: 14.2 (Feb. 2022), pp. 1–10.

[25] Alex Owen-Hill. "Job Shop vs Flow Shop: Can Robots Work for Both?" In: (2017).

[26] Yash P Gupta and Sameer Goyal. "Flexibility of manufacturing systems: Concepts and measurements". In: *European Journal of Operational Research* 43 (1989), pp. 119–135.

[27] Christian Weckenborg et al. "Flexibility in manufacturing system design: A review of recent approaches from Operations Research". In: *European Journal of Operational Research* 315.2 (June 2024), pp. 413–441.

[28] Taymaz Erol. "Types of flexibility in a single-machine production system". In: 27 (1989), pp. 1–9.

[29] Yoram Koren and Moshe Shpitalni. "Design of reconfigurable manufacturing systems". In: *Journal of Manufacturing Systems* 29.4 (Oct. 2010), pp. 130–141.

[30] Marta Pérez Pérez, Ana María Serrano Bedia, and María Concepción López Fernández. "A review of manufacturing flexibility: systematising the concept". In: 54.10 (May 2016), pp. 3133–3148.

[31] John P. Shewchuk and Colin L. Moodie. "Flexibility and manufacturing system design: An experimental investigation". In: *International Journal of Production Research* 38.8 (2000), pp. 1801–1822.

[32] Nigel Slack. "The Flexibility of Manufacturing Systems". In: 7 (1987), pp. 35–45.

[33] Kristina Höse et al. "Manufacturing Flexibility through Industry 4.0 Technological Concepts—Impact and Assessment". In: *Global Journal of Flexible Systems Management* 24.2 (June 2023), pp. 271–289.

[34] Carl Kjeldbjerg Lassen. *The business case of laser forming in micro/meso-scale manufacturing: A case study of Covi Precision*. Tech. rep. Aalborg University, 2024.

[35] Carl Kjeldbjerg Lassen. *APPENDIX APPENDIX 1 Case 1 Case 2 Material: Nickel-silver*. Tech. rep. Aalborg University, 2024.

[36] Suresh Kumar Krishnan. "Increasing the visibility of hidden failure costs". In: *Measuring Business Excellence* 10.4 (2006), pp. 77–101.

[37] David Ullman. *The Mechanical Design Process*. Mar. 2018. ISBN: 9780999357804.

Websites

[44] *High-Volume Production vs. Low-Volume Production*. URL: `https://resources.cadimensions.com/cadimensions-resources/high-volume-production-vs-low-volume-production`.

[45] *Common Problems in Sheet Metal Fabrication - Ruitai Mould*. URL: `https://www.rtprototype.com/common-problems-in-sheet-metal-fabrication/`.

[46] *Key Environmental Sustainability Issues in Sheet Metal Fabrication*. URL: `https://www.acra.com.au/key-environmental-sustainability-issues-in-the-sheet-metal-fabrication-industry/`.

[47] *Electroforming vs Similar technologies | Veco Precision*. URL: `https://www.vecoprecision.com/electroforming/electroforming-vs-other-technologies/`.

[48] *Sheet Metal Fabrication: A Comprehensive Guide*. URL: `https://geomiq.com/sheet-metal-guide/`.

[49] *Chemical Etching Process: 10 FAQs - Precision Micro*. URL: `https://www.precisionmicro.com/10-frequently-asked-chemical-etching-questions/`.

[50] *Chemical Etching: A Comprehensive Guide to Processes, Applications, and Techniques*. URL: `https://www.wevolver.com/article/chemical-etch`.

[51] *An Engineers' Guide to Sheet Metal Bending | Komaspec*. URL: https://www.komaspec.com/about-us/blog/guide-to-sheet-metal-bending/.

[52] *Welding Types and Their Uses – Simder Welder*. URL: https://www.ssimder.com/blogs/ssimderwelder/welding-types-and-their-uses?srsltid=AfmBOorfC_425z2ezX1-cbinzgLJmHidDx2UWJpkbMlVAqQtaxD8jKyo.

[53] *Comparing TIG and MIG Welders: Which is Right for You?* URL: https://esab.com/lv/eur_en/esab-university/blogs/comparing-tig-and-mig-welders-which-is-right-for-you/.

[54] *Plasma Arc Welding vs TIG Welding: What's the Difference?* URL: https://shop.machinemfg.com/plasma-arc-welding-vs-tig-welding-whats-the-difference/.

[55] *Which Industries Use Laser Engraving? An Up-close Look*. URL: https://livepositively.com/which-industries-use-laser-engraving-an-up-close-look/.

[56] Ravi Rao. *Gantry Systems: A Comprehensive Guide to Understanding and Implementing Gantry Technology*. 2023.

[57] *The Wonder of Galvo Laser Machines*. URL: https://omtechlaser.com/blogs/knowledge/the-wonder-of-galvo-laser-machines.

[58] *Laser Galvanometers: Types & Applications Explained 2025*. URL: https://opmtlaser.com/laser-galvanometers/.

[59] *KR FORTEC | KUKA AG*. URL: https://www.kuka.com/en-de/products/robot-systems/industrial-robots/kr-fortec.

[60] *Technical Data: BySprint Pro*. URL: https://portalimages.blob.core.windows.net/products/pdfs/0ulvvh2t_BySprintProBroshure.pdf.

[61] *XPlanar | Planar motor system | Beckhoff Automation*. URL: https://www.beckhoff.com/da-dk/products/motion/xplanar-planar-motor-system/.

[62] *BesCutter Mini Enclosed type Galvo 30W Laser Marking Machine*. URL: https://bescutter.com/collections/galvo-laser-engravers/products/30w-galvo-fiber-laser-marking-machine-mini-enclosed.

[63] *What is MoSCoW Prioritization? | Overview of the MoSCoW Method*. URL: https://www.productplan.com/glossary/moscow-prioritization/.

[64] *Bukning - Covi Precision*. URL: https://covi.dk/da/bukning/.

[65] *Madsfrohlich/VT4: VT4*. URL: https://github.com/Madsfrohlich/VT4.

[66] *Utilization Rate: What Is It and How To Calculate It*. URL: https://hubstaff.com/workforce-management/utilization-rate.

[67] *Customer Complaint Rate: Key Metric for Success*. URL: https://www.getcensus.com/ops_glossary/customer-complaint-rate-key-metric-for-success.

[68] *Used press brake tools & demonstration tools - ToolSystems24*. URL: https://www.toolsystems24.de/en/all-press-brake-tools/.

[69] *Formation-Machinery.com*. URL: https://formation-machinery.com/lazersafeguarding.html.

[70] *What are Technology Readiness Levels, and where is Wind Harvest in the process towards full commercialization of the first utility-scale H-type turbine? - Wind Harvest*. URL: https://windharvest.com/blog/faq-items/what-are-technology-readiness-levels-and-where-is-wind-harvest-in-the-process/.

A. LT-1 Performance

A.1 Cutting

COST

Machine	Price (AUD)	Price (EUR)	Type	Cutting bed	AVG. Price	Adjusted price	Radar plot value	Laser cutting + Plasma	
GENGSENG GS-CSE-3015 Fiber Laser Cutting Machine with 6KW Raycus.	$ 138,000.00	€ 82,951.80	Laser	3000x1500	€ 55,421.42	€ 12,315.87		Filter:	
GENGSENG GS-S-3015 Single table Laser cutting machine 3KW Raycus	$ 56,000.00	€ 33,661.60	Laser	3000x1500				Produceret	2024-2025
Exchange Table Metal Sheet Fiber Laser Cutting Machine 3KW	$ 109,000.00	€ 65,519.90	Laser	3000x1500			1	laser	minimum: 3kW
Single Table Laser Cutting Machine Open top 3KW, 1.5m x 3m Cutting Bed	$ 78,000.00	€ 46,885.80	Laser	3000x1500				Størrelse	mimimum 3000 mm
Farley EcoLASER 1.5x3m, 6.0kW Fiber Laser Machine Special!	$ 80,000.00	€ 48,088.00	Laser	3000x1500					
New BLAZE CNC Plasma Cutting Machine 240Volt Table 1500mm x 3000mm Cutting Area	$ 18,000.00	€ 10,819.80	Plasma	3000x1500	€ 14,877.23	€ 3,306.05		Waterjet:	
CNC 1530 Plasma Cutter With LGK Plasma Source	$ 22,000.00	€ 13,224.20	Plasma	3000x1500			5	produceret	2021+
Servo Drive - Water Bed CNC Plasma 1500mm x 3000mm With Free Software Package	$ 34,000.00	€ 20,437.40	Plasma	3000x1500				Størrelse	mimimum 3000 mm
1500mm x 3000mm Combination CNC Plasma & Engraving Head - Heavy Duty Build	$ 25,000.00	€ 15,027.50	Plasma	3000x1500					
2X3 METER Cantilever type waterjet cutting machine	$ 65,000.00	€ 39,071.50	WaterJet	3000x2000	€ 43,579.75	€ 7,548.54			
2x4 Meter Cantilever type waterjet cutting machine	$ 70,000.00	€ 42,077.00	Waterjet	4000x2000			3		
4x2 METER gantry type waterjet cutting machine	$ 75,000.00	€ 45,082.50	WaterJet	4000x2000					
Full Enclosed Waterjet Cutting Machine	$ 80,000.00	€ 48,088.00	WaterJet	3000x1500					

SPEED

Type	Speed	Radar Value	Link/Source
Laser	40 m/min (6 KW - 2 mm)	5	https://www.raymondlaser.com/laser-cutting-thickness-and-speed-chart/
Plasma	4.8 m/min (2 mm)	1	https://torchmate.com/metric-measures/Recommended-Cut-Speeds
Waterjet	9 m/min (Average)	2	https://www.wonlean.cn/Aseries.html?gad_source=1&gclid=Cj0KCQiA8fW9BhC8ARIsACwHqYqT9TT2gkAzo1N_EItf4WG1nU9OlBqqeqVkpyYUnvSglmq5hJPKp98aAljaEALw_wcB

VARIETY

Type	Vareity measure	Radar Value	Link/Source
Laser	Thin / wide range	3	https://geomiq.com/sheet-metal-guide/
Plasma	Medium / Only conductive metal	2	https://geomiq.com/sheet-metal-guide/
Waterjet	Thick / Almost all materials	5	https://geomiq.com/sheet-metal-guide/

KERF

Type	Kerf Quality	Radar Value	Link/Source
Laser	Execellent	5	https://www.wevolver.com/article/sheet-metal-manufacturing
Plasma	Good	3	https://www.wevolver.com/article/sheet-metal-manufacturing
Waterjet	Execellent	5	https://www.wevolver.com/article/sheet-metal-manufacturing

PRECISION/TOLERANCE

Type	Tolerances	Radar Value	Link/Source		
Laser	0.1-0.5 mm	5	https://www.in3dtec.com/the-differences-among-laser-cutting-waterjet-cutting-plasma-cutting-wire-cutting	https://geomiq.com/sheet-metal-guide/	https://www.komaspec.com/about-us/blog/guide-to-sheet-metal-bending/
Plasma	0.4-3.8 mm	2	https://www.in3dtec.com/the-differences-among-laser-cutting-waterjet-cutting-plasma-cutting-wire-cutting	https://geomiq.com/sheet-metal-guide/	
Waterjet	0.5-1.5	4	https://www.in3dtec.com/the-differences-among-laser-cutting-waterjet-cutting-plasma-cutting-wire-cutting	https://geomiq.com/sheet-metal-guide/	

VOLUME

Type	Volume	Radar Value	Link/Source		
Laser	High Volume (Thin)	5	https://www.zintilon.com/blog/edm-vs-laser-vs-waterjet-vs-plasma-cnc-cutting-contrast/	https://www.gdxql.com/news-comparison-of-laser-cutting-flame-cutting-water-jet-cutting-and-plasma-cutting.html	https://www.3erp.com/blog/laser-vs-water-jet-vs-plasma-cutting
Plasma	High Volume (Thick)	4	https://www.zintilon.com/blog/edm-vs-laser-vs-waterjet-vs-plasma-cnc-cutting-contrast/	https://www.3erp.com/blog/laser-vs-water-jet-vs-plasma-cutting	
Waterjet	Medium-High Volume	3	https://www.zintilon.com/blog/edm-vs-laser-vs-waterjet-vs-plasma-cnc-cutting-contrast/	https://www.gdxql.com/news-comparison-of-laser-cutting-flame-cutting-water-jet-cutting-and-plasma-cutting.html	https://www.3erp.com/blog/laser-vs-water-jet-vs-plasma-cutting

A.2 Forming

COST

Machine	Price (AUD)	Price (EUR)	Type	Tons	AVG. Price	Radar plot value
JTECH - New Pearson CNC Electro-Hydraulic Press brake 4100 mm x 250 Tonnes 5 Axis	$ 141,000.00	€ 84,755.10	Press Brake	250	€ 79,923.76	2
GHT 125-3000 Hydraulic CNC Press Brake	$ 147,000.00	€ 88,361.70	Press Brake	125		
4000mm x 175Ton CNC With Australian Made 2D-3D Graphical Controller, Laser Guards & Table Crowning	$ 78,850.00	€ 47,396.74	Press Brake	175		
Farley Press Brake 3.2m W - 250Tonne - 6+1 Axis - DA66T (Entry Special)	$ 165,000.00	€ 99,181.50	Press Brake	250		
160Ton Fixed & Sliding Head Industrial Shop Press - HUGE 1250mm Wide Frame	$ 12,850.00	€ 7,724.14	Stamp	160	€ 8,024.69	5
Combination Press, 200Ton with 20Ton Broach Press	$ 18,850.00	€ 11,330.74	Stamp	200		
110Ton Fixed & Sliding Head Industrial Shop Press - 900mm Frame Width	$ 10,850.00	€ 6,521.94	Stamp	110		
Heavy Duty Industrial 110Ton Hydraulic Workshop Press - Sliding Head & Vee Blocks	$ 10,850.00	€ 6,521.94	Stamp	110		
Schlebach Quadro Roll Forming System	$ 100,779.00	€ 60,578.26	Rollers		€ 76,558.95	3
ROLL FORMING MACHINES - BEST PRICES	$ 125,000.00	€ 75,137.50	Rollers			
Schlebach Quadro KS Profiling Machine	$ 140,690.00	€ 84,568.76	Rollers			
Quadro Heavy Duty Roll Form with Board & Battan profile	$ 142,990.00	€ 85,951.29	Rollers			
Laser - Only experiments on doing it (rough Estimate on price)	$ 1,000,000.00	€ 601,100.00	Laser		€ 601,000.00	1

SPEED

Type	Speed	Radar Value	Link/Source
Roll	High/continous production rates,	5	Manufacturing Engineering and Technology SI 6th Edition - Serope Kalpakjian Steven Schmid (2009)
Press brake	Somewhat manual	2	Manufacturing Engineering and Technology SI 6th Edition - Serope Kalpakjian Steven Schmid (2009)
Stamping	High production rates	3	Manufacturing Engineering and Technology SI 6th Edition - Serope Kalpakjian Steven Schmid (2009)
Laser	Incremental / prototyping	1	Experiments

VARIETY

Type	Thickness	Radar Value	Link/Source	
Roll	thin	3	Manufacturing Engineering and Technology SI 6th Edition - Serope Kalpakjian Steven Schmid (2009)	
Press brake	Thick 0.5 - 20 mm	5	Manufacturing Engineering and Technology SI 6th Edition - Serope Kalpakjian Steven Schmid (2009)	https://www.komaspec.com/about-us/blog/guide-to-sheet-metal-bending
Stamping	Thin 0.4 - 4 mm	3	Manufacturing Engineering and Technology SI 6th Edition - Serope Kalpakjian Steven Schmid (2009)	https://www.komaspec.com/about-us/blog/guide-to-sheet-metal-bending
Laser	Very thin	2		

VOLUME

Type	Volume	Radar Value	Link/Source	
Rollers	Very High (Continous)	5	https://www.wevolver.com/article/sheet-metal-manufacturing	
Press Brake	Moderate (Batch: Small to medium)	3	https://www.wevolver.com/article/sheet-metal-manufacturing	
Laser	mass Micro forming (1mm)	1	https://www.researchgate.net/publication/342095536_Recent_Developments_and_Trends_in_Sheet_Metal_Forming	
Stamping	High (Batch: large)	4	https://www.wevolver.com/article/sheet-metal-manufacturing	https://www.komaspec.com/about-us/blog/guide-to-sheet-metal-bending

COMPLEXITY

Type	Complexity	Numbers	Radar Value	Link/Source
Rollers	Designing and setting up roll forming equipment requires significant expertise, particularly in creating precise roller designs and configurations.	4 - 60 Steps (complex flower patterns)	5	https://www.dallan.com/en/news/what-is-roll-forming
Press Brake	Achieving high precision, especially for complex parts with multiple bends, demands skilled operators and careful setup.	Factors like: Springback, tonnage, bend radius, K-factor and bend length	3	https://www.komaspec.com/about-us/blog/guide-to-sheet-metal-bending
Laser	Only done on experimental setups		2	https://www.researchgate.net/publication/342095536_Recent_Developments_and_Trends_in_Sheet_Metal_Forming
Stamping	Some extremely intricate designs, Today, we use computer-aided methods (CAD) to create precise and complex dies. This technology allows for intricate designs that would have been impossible or too costly to produce in the past.		4	https://www.worthyhardware.com/news/what-is-metal-stamping

SIMPLICITY

Type	Simplicity (Generic or costum made)	Numbers (tooling cost)	Radar Value	Link/Source
Rollers	Each set of rolls is custom-designed for a specific profile, Individual rolls are designed using specialized software	high	1	https://www.wevolver.com/article/sheet-metal-manufacturing
Press Brake	Specialized tooling, such as gooseneck punches or hemming dies, allows for complex bend profiles and special operations.	Low To Modrate	3	https://www.wevolver.com/article/sheet-metal-manufacturing
Stamping	specialized tools called dies to shape the metal, Calculating the forces and stresses involved in each operation Designing the die geometry to achieve the desired part shape	High	1	https://www.wevolver.com/article/sheet-metal-manufacturing
Laser	Laser forming is a highly flexible and iterative contactless thermomechanical forming process that utilises a defocused laser beam to induce material shortening and bending.	Moderate	5	https://www.tandfonline.com/doi/full/10.1080/00207543.2023.2241565

A.3 Welding

COST					
Machine	**Price (USD)**	**Price (USD)**	**Price (EUR)**	**Type**	**Radar plot value**
	Min	Max	Total Minimum	Tatal Maximum	
MIG - Energy	$ 1,000.00	$ 2,000.00	€ 6,204.90	€ 12,887.10	
MIG - Consumables	$ 5,000.00	$10,000.00			4
MIG - Maintenance	$ 500.00	$ 1,500.00			
TIG - Energy	$ 2,000.00	$ 3,000.00	€ 12,887.10	€ 19,569.30	
TIG - Comsumables	$ 10,000.00	$15,000.00			3
TIG - Maintenance	$ 1,500.00	$ 2,500.00			
RSW	$ 250.00	$ 1,000.00	€ 238.65	€ 954.60	5
Plasma Arc Welding - General cost of production	$ 14,800.00	$29,630.00	€ 14,128.08	€ 28,284.80	2
Laser - Energy	$ 3,000.00	$ 6,000.00	€ 5,250.30	€ 36,274.80	
Laser - Consumables	$ 1,500.00	$ 7,000.00			1
Laser - Maintenence	$ 1,000.00	$25,000.00			

SPEED			
Type	**Speed**	**Radar Value**	**Link/Source**
MIG	290 mm/min (slow)	2	https://www.proquest.com/scholarly-journals/comparative-study-fsw-mig-tig-welding-aa5083-h111/docview/2843081517/se-2?accountid=8144
TIG	240 mm/min (slower)	1	https://www.proquest.com/scholarly-journals/comparative-study-fsw-mig-tig-welding-aa5083-h111/docview/2843081517/se-2?accountid=8144
RSW /Spor	very high speed	5	https://www.wevolver.com/article/sheet-metal-manufacturing
Arc	Medium	3	https://www.wevolver.com/article/sheet-metal-manufacturing
Laser	high speed	4	https://blog.hirebotics.com/types-of-welding-processes#electron-laser-welding

VARIETY			
Type	**Thickness and materials Geometries**	**Radar Value**	**Link/Source**
MIG	0.5-13mm	5	https://www.wevolver.com/article/sheet-metal-manufacturing
TIG	0.2-6 mm / Most metals	3	https://www.wevolver.com/article/sheet-metal-manufacturing
RSW /Spor	0.5-3 mm	2	https://www.wevolver.com/article/sheet-metal-manufacturing
Arc	0.5-6 mm	3	https://www.wevolver.com/article/sheet-metal-manufacturing
Laser	0.05-10mm / Most metals	4	https://covi.dk/en/Competencies/Laser-Welding-Metal

AUTOMATION			
Type	**Automation potential current and future**	**Radar Value**	**Link/Source**
MIG	High	4	https://www.wevolver.com/article/sheet-metal-manufacturing
TIG	Moderate	2	https://www.wevolver.com/article/sheet-metal-manufacturing
RSW /Spor	Very high	5	https://www.wevolver.com/article/sheet-metal-manufacturing
Arc	High	3	https://www.wevolver.com/article/sheet-metal-manufacturing
Laser	Very high	5	

POST PROCESSING			
Type	**Post procesing needed**	**Radar Value**	**Link/Source**
MIG	Remove slag grind weld bead	1	https://www.thecrucible.org/guides/welding-2/types-of-welding/
TIG	Minimal	3	https://www.thecrucible.org/guides/welding-2/types-of-welding/
RSW /Spot	Genarally none	5	https://www.codinter.com/en/spot-welding-a-complete-guide/
Arc	Minimal	3	https://www.thecrucible.org/guides/welding-2/types-of-welding/
Laser	minimal to none	4	https://www.laserline.com/en-int/laser-welding/?utm_source=Google%20Ad&utm_medium=cpc&utm_campaign=application_areas_en_eu&utm_content=laser-welding&creative=492680572024&keyword=%2Blaser%20%

A.4 Finishing

COST

Method	Tools	Machine	Total	Note	Radar value
Laser		$ 11,366.67	€ 10,850.62	Complete	3
Rotary	$ 150.00	€ 10,300.00	€ 10,443.19	Tool + milling	3
Burnising	$ 60.00	€ 8,592.00	€ 8,649.28	Tool + lathe	5
Diamond drag	$ 65.99	€ 10,300.00	€ 10,362.99	Tool + milling	3

SPEED

Type	Speed	Radar Value	Link/Source
Laser	40-60 mm/s And generally much faster than mechanical methods	5	https://dplaser.com/what-laser-power-to-engrave-metal/ https://www.accumet.com/resources/3402-tb-laser-etching-vs-mech-engraving.pdf
Diamond	Slingle stroke	3	https://www.xometry.com/resources/blog/how-metal-engraving-works
Burninshing	Multiple strokes	2	https://www.xometry.com/resources/blog/how-metal-engraving-works
Rotary	Fast rotating spinde there by fast feed rate	3	https://www.xometry.com/resources/blog/how-metal-engraving-works

VARIETY

Type	Procceses	Radar Value	Link/Source
Laser	Cleaning, Engraveing, Marking	5	https://www.xometry.com/resources/blog/how-metal-engraving-works/
Diamond	Engraveing	1	https://www.xometry.com/resources/blog/how-metal-engraving-works/
Burninshing	Engraveing, polishing	3	https://www.xometry.com/resources/blog/how-metal-engraving-works/
Rotary	Engraveing, (cleaning)*	2	https://www.xometry.com/resources/blog/how-metal-engraving-works/

RESOULUTION

Type	Resolution (smallest posible detail)	Radar Value	Link/Source
Laser	25 micron	5	https://www.jtvmfg.com/blog/how-precise-is-laser-cutting/
Diamond	50 micron	4	https://www.jpplus.com/resources/basic-engraving-techniques-diamond-drag-
Burninshing	125 - 250 micron	2	https://www.antaresinc.net/FactBRN.html
Rotary	125 micron	2	Similar to Burnishing

SURFACE

Type	Surface Roughness	Radar Value	Link/Source
Laser	Varying depending on use case	3	https://www.xometry.com/resources/blog/how-metal-engraving-works/
Diamond	Hard diamond tools leaves clean marks, however not suited for polishing	4	https://www.xometry.com/resources/blog/how-metal-engraving-works/
Burninshing	Can be used for polishing, meaning low surface rougness	5	https://www.researchgate.net/publication/316239007_Surface_improvement_of_shafts_by_the_diamond_burnishing_and_ultrasonic_burnishing_techniques
Rotary	Generaly course tools.	2	https://www.xometry.com/resources/blog/how-metal-engraving-works/

B. Experimental Findings

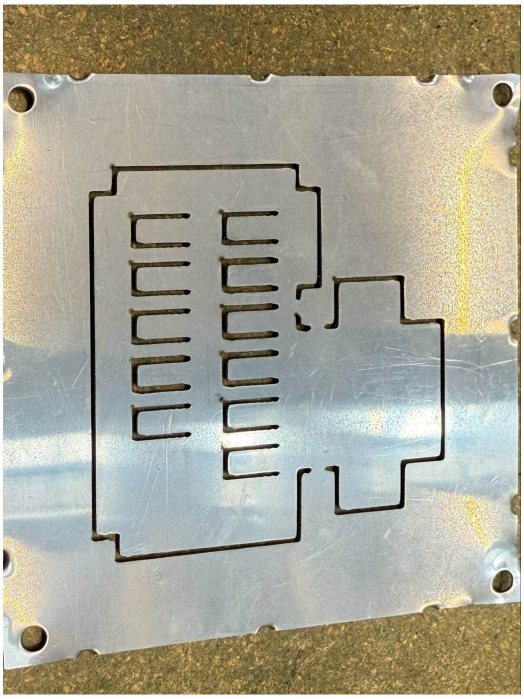
This appendix contains documentation and findings regarding the experiments performed to achieve the presented results.

B.1 Assessment Part - Industrial Relevant Part

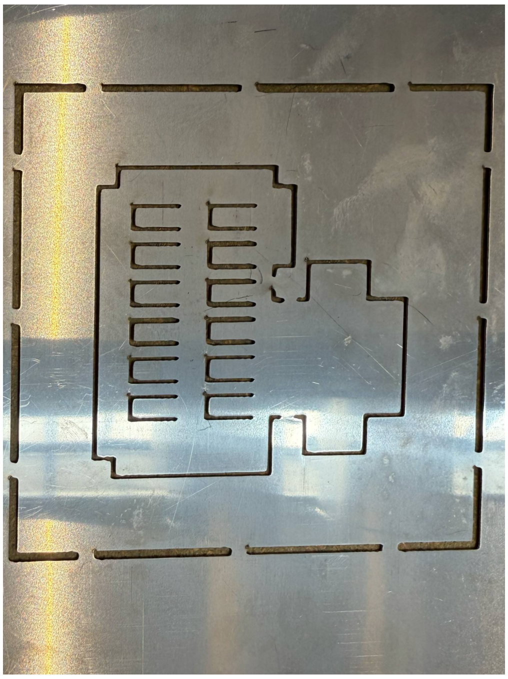
In evaluating the processing of the assessment part, three key categories have been identified as influential to overall performance and efficiency: (1) cutting template (initial production phase – lead time), (2) fixture design and initial test (setup phase – lead time), and (3) forming of the actual part (production phase). This appendix provides a detailed account of the findings, observations, and reflections related to each processing step. The intention is to facilitate reproducibility and offer insights for further optimisation by future users or researchers seeking to improve the design and processing methodology of similar parts.

B.1.1 Cutting Template

During the initial production phase of the assessment part, it was observed that the use of Approach Two, as outlined in Chapter 6, is significantly influenced by the sequencing and placement of fixation points. This strategy presents challenges related to overhang, which can lead to processing issues. Specifically, during laser forming of the part, production phase three, a considerable amount of heat is introduced into the material, increasing the risk of warping, particularly in cases of excessive overhang, suboptimal fixation point placement, or insufficient cooling.
Additionally, sequencing of the cutting operations proved critical. The use of high-pressure assist gas during cutting may cause surface displacement if the part is not adequately constrained. To mitigate this, a deliberate cutting sequence was employed: the process began from the interior of the part and progressed outward toward the fixation points. This approach was chosen to stabilise the part throughout the cutting process and minimise the risk of positional shifts or deformation. Differences in cutting randomly and using the sequence explained can be seen in Figure B.1:



(a) Example of a suboptimal cutting sequence leading to an incomplete cut and different spacings, because of an emergency stop.



(b) Example of an optimised cutting sequence starting from internal features and progressing outward toward fixation points.

Figure B.1: Comparison of cutting sequences for the assessment part, highlighting the importance of task order and fixation approach in preventing thermal distortion.

B.1.2 Fixture Design and Initial Tests

The setup phase encompassed the design of the fixture and the execution of initial tests to establish the open-loop control parameters for the subsequent production phase. As described in Chapter 6, the fixture was developed using a rapid prototyping approach—specifically, 3D printing.

Initially, it was anticipated that 3D-printed fixtures would be unsuitable for laser forming due to the significant heat generated during processing. However, by employing approach two, which involves cutting a template with integrated fixation points prior to forming, heat exposure to the fixture was effectively eliminated. This ensured the part remained adequately constrained during forming without transferring thermal loads to the fixture. Consequently, the 3D-printed fixture proved to be a viable solution under this processing strategy.

To establish the appropriate parameters for the open-loop control of the assessment part production, a series of preliminary experiments were conducted. These tests investigated the influence of varying bend radii, laser power levels, scan speeds, and the effect of using single versus multiple scan lines for forming operations.

All experiments were performed using a 40 [mm] wide, 0.5 [mm] thick stainless steel plate (AISI 304). The initial phase focused on identifying suitable laser settings using a single scan line. Through this, a laser power of 100 [W] and a scan speed of 50 [$\frac{mm}{s}$] were determined to be optimal, as these parameters resulted in minimal to no thermal distortion on the reverse side of the material.
Subsequently, angle measurements revealed that a single scan produced an average bend of approximately 2° ±0.2°. Based on this, the total bend angle of 90° was achieved by performing up to 45 scan passes at different radii (5 [mm], 2 [mm], and 1 [mm]). These findings formed the basis for defining the open-loop control strategy. A summary of the scan strategy results is provided in Table B.1.

Scan Strategy Comparison for Laser Forming

Radii	Number of Scans	Total Bend Angle [°]	Angle per Scan [°]
5	39	90	2.5
2	42	91	2.2
1	45	90	2.0

Table B.1: Comparison of laser forming strategies using different radii and scan counts to achieve target bend angles.

These parameters is used to produce the actual assessment part.

B.1.3 Forming the Actual Part

During the initial forming iterations of the assessment part, several key observations were made that informed the final process approach. One of the most critical findings concerned the sequencing of laser cutting in relation to the forming process. It became evident that bending operations involving features with significant overhang needed to be prioritised early in the forming sequence. This approach was necessary to minimise heat accumulation in the material, which could otherwise lead to excessive warping and thermal distortion. By changing the forming sequence in this manner, the structural integrity and dimensional accuracy of the part were significantly improved. These findings contributed to the refinement of the overall process plan. An image of the first formed iteration of the assessment part is shown in Figure B.2.

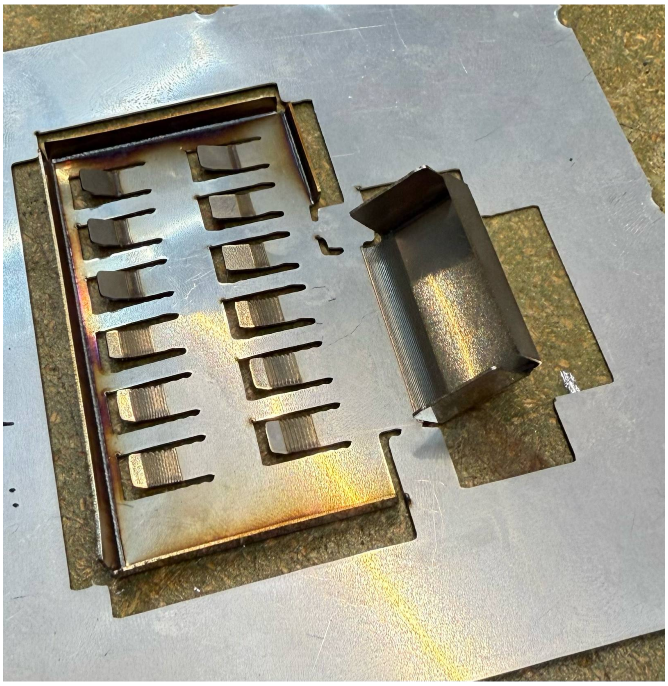


Figure B.2: First iteration of the assessment part showing the effects of non-optimised forming sequence. Warping and thermal distortion are visible, highlighting the importance of proper process planning.

In the first iteration, a dwell time of 1.5 [s] combined with minimal external cooling resulted in excessive thermal distortion of the part. This highlighted the sensitivity of the process to heat accumulation. Subsequent changes to the forming sequence reduced warping slightly, although the results remained suboptimal. To further investigate the impact of thermal management, three additional iterations were conducted, each with varying dwell times and levels of external cooling. The aim was to evaluate the extent to which these parameters influenced the mitigation of warping and overall thermal distortion. The outcomes of these tests are illustrated in Figure B.3.

Figure B.3: Results from varying dwell times and external cooling. From left to right: (1) 3-second cooling time with excessive warping and significant thermal distortion, (2) 6-second dwell time with increased external cooling resulting in notable reduction of warping and minimal distortion, and (3) 8-second dwell time with similar cooling, showing no significant improvement compared to the second test.

As observed in Figure B.3, the implementation of increased dwell times and enhanced external cooling significantly improved the part quality, both in terms of reduced warping and minimised thermal distortion on the backside. The first iteration applied a cooling time of 3 seconds, the second 6 seconds, and the final iteration 8 seconds. Based on these results, the final processing parameters—8-second dwell time and increased external cooling—were selected for the production of six test parts, which form the basis for the evaluation presented in Chapter 7.

It should be noted that when using an open-loop control approach, several potential sources of error must be considered. These include variations in material properties, differences in cut sheet placement (e.g., edge versus centre), and inconsistencies in the angle produced per scan line, which is extrapolated to achieve a 90° bend. Following the last set of trials, the final iteration was evaluated to confirm whether adjustments to the number of scan lines were necessary. If not, the six-part batch was produced to test the system's capability for the intended application in rapid prototyping and low-volume production.

B.2 Conference Article

During the experimental evaluation of the different laser processing systems, several noteworthy observations were made. These findings are categorised according to each system and pertain to aspects such as power control, coding format, motion limitations, and other system-specific considerations. The observations provide additional insight into the practical performance and operational constraints encountered during the study.

B.2.1 Robotic Laser Processing System (Toolhead Manipulation)

The primary observation regarding the robotic laser processing system concerns its positioning accuracy during engraving operations. Due to the significant mass that must be moved in complex patterns, the system exhibited poor surface quality, characterised by surface burning and the formation of small burn marks each time the robot changed direction. In contrast, for simpler, repetitive motions such as forming, the robotic system demonstrated better performance compared to the other evaluated systems, particularly in terms of process tolerance, an inherent advantage of robotic platforms in such applications, as the robot has high repeatability.

It is important to note that the median bend angle achieved during forming was

94.25°, which does not imply a deficiency in the system's forming capabilities. Instead, this deviation is attributed to incorrect process parameters, such as insufficient laser power or an inappropriate number of scan lines selected during the experimental setup.
In addition to the median bend angle, further issues were identified with power control of the laser system. Specifically, the system exhibited instability at lower power outputs, as it is rated for 3 [kW]. When a setpoint of 600 [W] was commanded, the actual measured output ranged between 260 [W] and 280 [W]. Moreover, the laser output was internally recorded in units of kilowatts, limiting measurement precision to increments of approximately 10 [W]. This lack of fine control negatively impacted process consistency. For improved performance, a more precise method of wattage control should be considered in future implementations.

B.2.2 Arges Galvometer Laser Processing System (Toolhead Manipulation)

A significant observation from the experiments conducted using the Arges Galvanometer Laser Processing System relates to discrepancies in its effective workspace. Although the system specifications indicate a workspace of 300×300 [mm], experimental results showed that the practically usable workspace, providing acceptable engraving quality and laser beam shape, is limited to approximately 200×200 [mm].

Additionally, variations in laser spot geometry were noted across the workspace. At the workspace centre, the laser spot exhibited a circular profile, while moving towards the outer regions, it progressively transformed into an elliptical shape. This change in geometry likely contributes to the higher tolerance variations observed during forming processes, as forming operations typically require substantial laser spot movement across the workspace and a stable line energy put into the material, which varies according to the shape or size of the spot size.

A notable observation regarding the coordinate system and control method of the processing system is its reliance on straight-line segments for motion control, which suggests that the contour-following engraving approach may not be optimal. The primary finding from experimentation was a misalignment of approximately 3° between the system's coordinate system and the fixture. Due to this angular skew and the segment-based control method, additional calibration was required to ensure proper alignment between the processing system and the fixture, thus ensuring accurate processing outcomes.

Another key observation during experimentation concerned the stability of the processing system at varying processing speeds. Instabilities became evident at higher speeds, particularly during speed calibration trials aimed at optimising engraving quality. At maximum speed, engraving quality deteriorated significantly, becoming illegible. However, at lower processing speeds—approximately 200 [$\frac{mm}{s}$]or below—the system stabilised, consistently producing acceptable engraving results. Additionally, similar power control issues identified previously in the robotic system were observed here, as both systems share an identical method for controlling laser power output.

B.2.3 Magnetic Levitation Table Laser Processing System (Workpiece Manipulation)

For the magnetic levitation system, the primary observations concerned the fixation method and the limited workspace. The fixture, fabricated from 3D-printed plastic, exhibited deformation during the initial forming processes due to heat exposure from the laser. To mitigate this issue, tinfoil was applied to protect the plastic surfaces in contact with the workpiece. Regarding the workspace, the effective processing area was limited to 80×80 [mm], which constrained certain operations and necessitated manual intervention to reposition the workpiece between different processing stages.

C. Mail Correspondence with Industry Stakeholder

Outlook

Fw: Sprøgsmål til COVI

From Morten Kristiansen <morten@mp.aau.dk>
Date Tue 20-May-25 11:46 AM
To Mads Augustinus Frøhlich <mfrahl20@student.aau.dk>; Mads Holm Andersen <mhan20@student.aau.dk>

Hej 2 x Mads

Hermed svar fra COVI.

Mvh.
Morten

From: Henrik Hjelmsø <hhj@covi.dk>
Sent: Tuesday, May 20, 2025 11:32 AM
To: Morten Kristiansen <morten@mp.aau.dk>
Subject: SV: Sprøgsmål til COVI

Hej Morten

Hermed nogle af vores produktions data.

Vi producere i strips af 5 stk. enheder pr. strip.
Vi producere 1.000 – 2.000 enheder pr. ordre.
Vi har ca, 5 % spild, så der igangsættes typisk f.eks. 2.150 stk. ved en ordre på 2.000 stk.
Kvaliteten er defineret på tegningen.

Step 1, Laserskæring på en laserskæremaskine:
Opstilling 1 time (maskine + operatør)
Skæring pr. stk. 11 sekunder (maskine)
Afgratning udføres manuelt mens maskinen skære, derfor 11 sek. Pr. stk. (operatør)

Step 2, Bukning på bukke maskine:
Opstilling 1 time (maskine + operatør)
Bukning pr. stk. 10 sek. (maskine + operatør)

Kontrol:
Opstilling på målemaskine 1 time
Kontrol pr. ordre 1-2 timer

Jeg håber det er gode og brugbare data til den videre analyse.

Med venlig hilsen / Best regards

Henrik Hjelmsø

CEO

direct: +45 41 966 550
e-mail: hhj@covi.dk

Fra: Morten Kristiansen <morten@mp.aau.dk>
Sendt: 14. maj 2025 12:44
Til: Henrik Hjelmsø <hhj@covi.dk>
Emne: Sprøgsmål til COVI

Hej Henrik

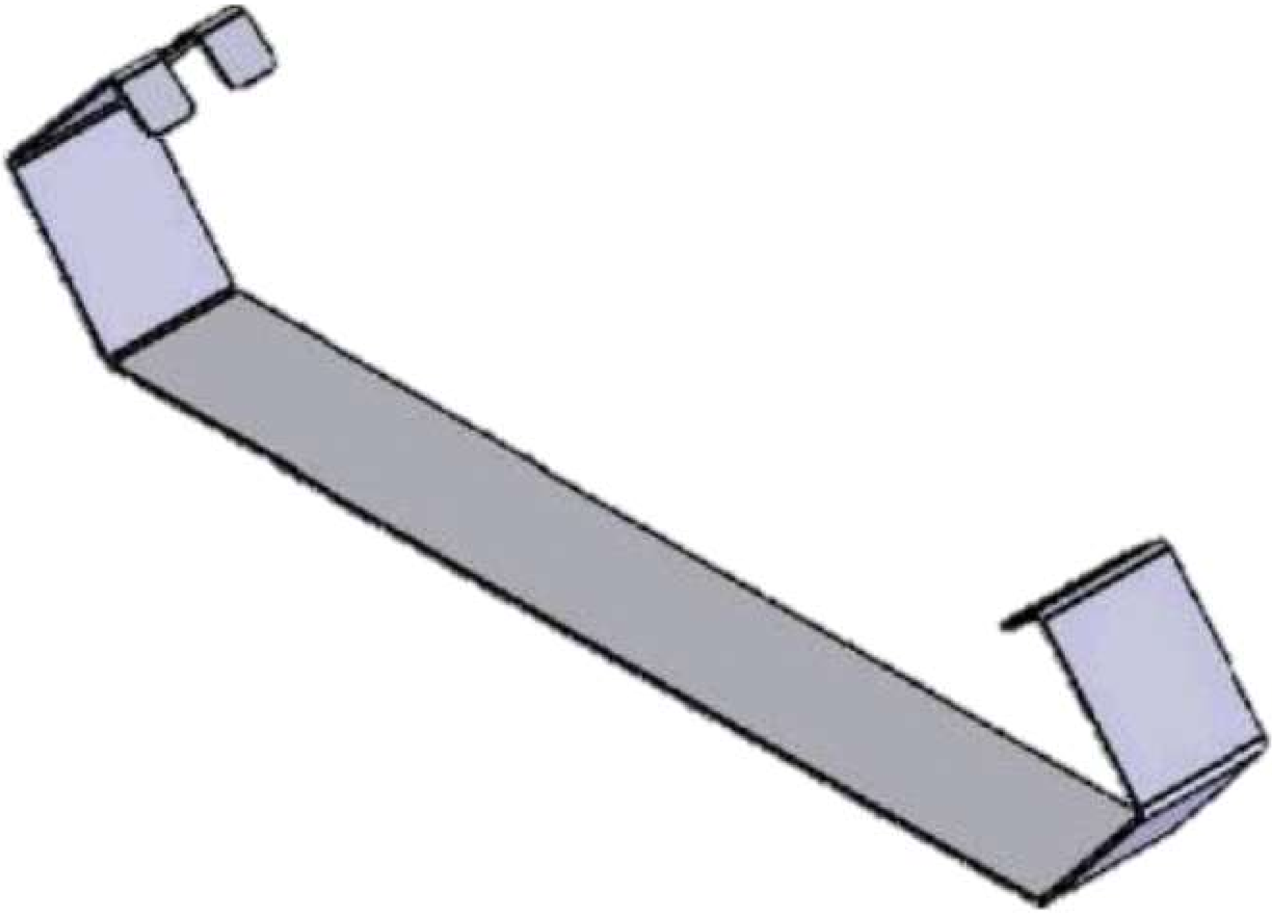
De studerende har nu været grundigt igennem det tidligere arbejde og har nogle ekstra spørgsmål, som de håber at du vil være behjælpelige med. De har derfor skrevet nedenstående og håber at vi kan have et kort møde omkring dette.

Mvh. Morten

Hej COVI,

Vi vil gerne foreslå et møde, hvor vi kan drøfte krav, kvalitet og produktionstid med jer. Vi håber at kunne præsentere vores kravspecifikation og høre, om det er noget, I kan genkende eller om i har noget i evt. vil tilføje. Derudover kunne vi tænke os at få en dialog omkring jeres fokus på kvalitet, og hvilke målemetoder I bruger for at vurdere den. Vi er også interesserede i at høre, hvor mange enheder der skrottes grundet de ikke opfylder kvalitetskriterierne for jeres kunder.

Endelig vil vi gerne tale om den tid, I bruger pr. ordre. Vi har forstået, at I producerer maximum cirka 2000 enheder per ordre, og vi vil gerne høre, hvor lang tid I cirka bruger på at producere en sådan ordre. Hvis muligt, vil vi også gerne vide, hvor mange maskiner der er i brug for at producere en enkelt enhed som vidst på billedet under.



På forhånd tak!

AALBORG UNIVERSITET

Med venlig hilsen | Best regards | Mads Augustinus Frøhlich

Studerende | Fakultet for Tech and Engineering

Mekanik og Produktion - (Virksomhedsteknologi) Manufactoring tehcnology

Tlf.: (+45) 20662039 **| Email**: mfrahl20@student.aau.dk **| Web**: www.aau.dk

Aalborg Universitet | Fibigerstræde 14 **|** Aalborg

D. Cost of Systems

D.1 Magnetic Levitation Price Estimation

Full Scale							
Inquiry (DKK)				**Inquiry (EUR)**			
	Price [DKK]	QTY	Total		Price [EUR]	QTY	Total
Laser system				**Laser system**			
Laser 1000 W	400,000.00 kr.	1	400,000.00 kr.	Laser 1000 W	€ 53,600.00	1	€ 53,600.00
Laser 500 W	300,000.00 kr.	1	300,000.00 kr.	Laser 500 W	€ 40,200.00	1	€ 40,200.00
Xplanar				**Xplanar**			
Mover	4,205.80 kr.	25	105,145.00 kr.	Mover	€ 563.58	25	€ 14,089.43
Tile	27,455.00 kr.	36	988,380.00 kr.	Tile	€ 3,678.97	36	€ 132,442.92
IPC	76,243.20 kr.	1	76,243.20 kr.	IPC	€ 10,216.59	1	€ 10,216.59
I/O cards (all)				**I/O cards (all)**			
EK1100	857.78 kr.	1	857.78 kr.	EK1100	€ 114.94	1	€ 114.94
EL9227-5500	857.78 kr.	6	5,146.68 kr.	EL9227-5500	€ 114.94	6	€ 689.66
EL1004	201.36 kr.	6	1,208.16 kr.	EL1004	€ 26.98	6	€ 161.89
EL2502*	700.00 kr.	1	700.00 kr.	EL2502*	€ 93.80	1	€ 93.80
EL4004*	1,000.00 kr.	1	1,000.00 kr.	EL4004*	€ 134.00	1	€ 134.00
Misc				**Misc**			
ZK1096-8181-0005	405.03 kr.	30	12,150.90 kr.	ZK1096-8181-0005	€ 54.27	30	€ 1,628.22
ZK1096-8181-0050	527.43 kr.	6	3,164.58 kr.	ZK1096-8181-0050	€ 70.68	6	€ 424.05
ZC2000-0000-0017	4,958.90 kr.	6	29,753.40 kr.	ZC2000-0000-0017	€ 664.49	6	€ 3,986.96
Fixture				**Fixture**			
3d Print	50.00 kr.	25	1,250.00 kr.	3d Print	€ 6.70	25	€ 167.50
Sum			**1,924,999.70 kr.**	Sum			**€ 257,949.96**
Salvage value	Resell value	10%	192,499.97 kr.	Salvage value	Resell value	10%	€ 25,795.00
Depreciation	Period years	10	**173,249.97 kr.**	Depreciation	Period years	10	**€ 23,215.50**

Bend only							
Inquiry (DKK)				**Inquiry (EUR)**			
	Price [DKK]	QTY	Total		Price [EUR]	QTY	Total
Laser system				**Laser system**			
Laser 500 W	300,000.00 kr.	1	300,000.00 kr.	Laser 500 W	€ 40,200.00	1	€ 40,200.00
Xplanar				**Xplanar**			
Mover	4,205.80 kr.	8	33,646.40 kr.	Mover	€ 563.58	8	€ 4,508.62
Tile	27,455.00 kr.	15	411,825.00 kr.	Tile	€ 3,678.97	15	€ 55,184.55
IPC	76,243.20 kr.	1	76,243.20 kr.	IPC	€ 10,216.59	1	€ 10,216.59
I/O cards (all)				**I/O cards (all)**			
EK1100	857.78 kr.	1	857.78 kr.	EK1100	€ 114.94	1	€ 114.94
EL9227-5500	857.78 kr.	6	5,146.68 kr.	EL9227-5500	€ 114.94	6	€ 689.66
EL1004	201.36 kr.	6	1,208.16 kr.	EL1004	€ 26.98	6	€ 161.89
EL2502*	700.00 kr.	1	700.00 kr.	EL2502*	€ 93.80	1	€ 93.80
EL4004*	1,000.00 kr.	1	1,000.00 kr.	EL4004*	€ 134.00	1	€ 134.00
Misc				**Misc**			
ZK1096-8181-0005	405.03 kr.	15	6,075.45 kr.	ZK1096-8181-0005	€ 54.27	15	€ 814.11
ZK1096-8181-0050	527.43 kr.	3	1,582.29 kr.	ZK1096-8181-0050	€ 70.68	3	€ 212.03
ZC2000-0000-0017	4,958.90 kr.	3	14,876.70 kr.	ZC2000-0000-0017	€ 664.49	3	€ 1,993.48
Fixture				**Fixture**			
3d Print	50.00 kr.	8	400.00 kr.	3d Print	€ 6.70	8	€ 53.60
Sum			**853,561.66 kr.**	Sum			**€ 114,377.26**
Salvage value	Resell value	10%	85,356.17 kr.	Salvage value	Resell value	10%	€ 11,437.73
Depreciation	Period years	10	**76,820.55 kr.**	Depreciation	Period years	10	**€ 10,293.95**

Figure D.1: Inquiry of Magnetic levitation systems.

D.2 Conventional Price Estimation

Full Scale							
Inquiry (DKK)				**Inquiry (EUR)**			
	Price	QTY	Total		Price	QTY	Total
Cutting				**Cutting**			
Laser	412,886.45 kr.	1	412,886.45 kr.	Laser	€ 55,421.00	1	€ 55,421.00
Forming				**Forming**			
Press brake min	353,105.64 kr.	1	353,105.64 kr.	Press brake min	€ 47,396.73	1	€ 47,396.73
Welding				**Welding**			
MIG min	46,219.80 kr.	1	46,219.80 kr.	MIG min	€ 6,204.00	1	€ 6,204.00
Engrave				**Engrave**			
Rottery	77,204.35 kr.	1	77,204.35 kr.	Rottery	€ 10,363.00	1	€ 10,363.00
Automation				**Automation**			
KUKA R2500	600,000.00 kr.	4	2,400,000.00 kr.	KUKA R2500	€ 78,000.00	4	€ 312,000.00
Sum			**3,289,416.24 kr.**	Sum			**€ 431,384.73**
Salvage value	Resell value	20%	657,883.25 kr.	Salvage value	Resell value	20%	€ 86,276.95
Depreciation	Period years	10	**263,153.30 kr.**	Depreciation	Period years	10	**€ 34,510.78**
Tools				**Tools**			
Tools (Punches)	3,680.30 kr.	13	47,843.90 kr.	Tools (Punches)	€ 494.00	13	€ 6,422.00
Tools (Dies)	1,788.00 kr.	13	23,244.00 kr.	Tools (Dies)	€ 240.00	13	€ 3,120.00
Sum			**71,087.90 kr.**	Sum			**€ 9,542.00**
Depreciation	Period years	1	**71,087.90 kr.**	Depreciation	Period years	1	**€ 9,542.00**

Bend only							
Inquiry (DKK)				**Inquiry (EUR)**			
Forming				**Forming**			
Press brake min	353,105.64 kr.	1	353,105.64 kr.	Press brake min	€ 47,396.73	1	€ 47,396.73
Automation				**Automation**			
KUKA R2500	600,000.00 kr.	1	600,000.00 kr.	KUKA R2500	€ 78,000.00	1	€ 78,000.00
Sum			**953,105.64 kr.**	Sum			**€ 125,396.73**
Salvage value	Resell value	20%	190,621.13 kr.	Salvage value	Resell value	20%	€ 25,079.35
Depreciation	Period years	10	**76,248.45 kr.**	Depreciation	Period years	10	**€ 10,031.74**
Tools				**Tools**			
Tools (Punches)	3,680.30 kr.	13	47,843.90 kr.	Tools (Punches)	€ 494.00	13	€ 6,422.00
Tools (Dies)	1,788.00 kr.	13	23,244.00 kr.	Tools (Dies)	€ 240.00	13	€ 3,120.00
Sum			**71,087.90 kr.**	Sum			**€ 9,542.00**
Depreciation	Period years	1	**71,087.90 kr.**	Depreciation	Period years	1	**€ 9,542.00**

Figure D.2: Inquiry of Dedicated systems.