Manufacturing Concepts for Laser Processing

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Abstract
Through a literature study on laser manufacturing an analysis is conducted to explore the four processes: Laser bending, cutting, drilling, and welding. Afterwards, an analysis of the production of a partnership company, is conducted. Based on these analyses a problem statement with an associated requirement specifications is formulated. Additionally, assumptions and delimitations of the project are formulated. Based on the problem statement different conceptual suggestions are generated and evaluated. One of these concepts are chosen for further development. This is done by implementing the concept in a virtual production.

Keywords: Laser processing, Virtual commissioning, Process integration, Discrete event simulation, Operation analysis

Nomenclature

P_δ	Power density $\left[\frac{\mathrm{W}}{\mathrm{m}^2}\right]$
v_{drill}	Drill velocity $[\frac{\mathrm{m}}{\mathrm{s}}]$
η	Absorption coefficient
L_v	Latent heat of vaporisation $\left[\frac{\mathrm{J}}{\mathrm{kg}}\right]$
T_v	Vaporisation temperature of material [K]
ρ	Density $\left[\frac{\mathrm{kg}}{\mathrm{m}^3}\right]$
C_p	Specific heat capacity $\left[\frac{\mathrm{J}}{\mathrm{kg}\cdot\mathrm{K}}\right]$
T_0	Initial temperature of material [K]
L_f	Latent heat of fusion $\left[\frac{\mathrm{J}}{\mathrm{kg}}\right]$
P	Power [W]
v_{cut}	Cut velocity $[\frac{\mathrm{m}}{\mathrm{s}}]$
r_{beam}	Radius of laser beam [m]
s_t	Material thickness [m]
Δh_m	Required increase in enthalpy $\left[\frac{\mathrm{J}}{\mathrm{kg}}\right]$
r_f	Reflectivity coefficient
v_{weld}	Welding velocity $[\frac{\mathrm{m}}{\mathrm{s}}]$
w_{weld}	Welding width [m]
β	Conduction coefficient
T_m	Melting temperature [K]
a_{diff}	Thermal diffusivity $\left[\frac{\mathrm{m}^2}{\mathrm{s}}\right]$
d_B	Beam diameter [m]
F_0	Fourier number. Between 0.2 and 0.4
t_c	cooling time [s]
v_{bend}	Bending velocity $\left[\frac{\mathrm{m}}{\mathrm{s}}\right]$
α_{th}	Coefficient of thermal expansion $[\mathrm{K}^{-1}]$
θ_b	Incremental bend angle [rad]
κ	Material thermal conductivity $\left[\frac{\mathrm{W}}{\mathrm{m}\cdot\mathrm{K}}\right]$

1. Introduction

Lasers have multiple functionalities and is a technology in evolution. Some of the functionalities of lasers are: Laser surgery, telecommunications, weaponry and material processing [1]. Material processing capabilities of lasers are considered in this project, and it is based upon what the group assumes to be possible five years from now. Lasers are capable of several material manufacturing processes such as: bending, cutting, drilling, and welding. Cutting and drilling are technologies that have had longer industrial application than welding and bending. Therefore bending and welding are still technologies in development. Integrating lasers in a manufacturing setup capable of multiple material manufacturing processes in a compact production cell is the focus of the project. Additional, the focus is on low-volume/high variety production, where low-volume is chosen to be batch sizes of 1-100 products.

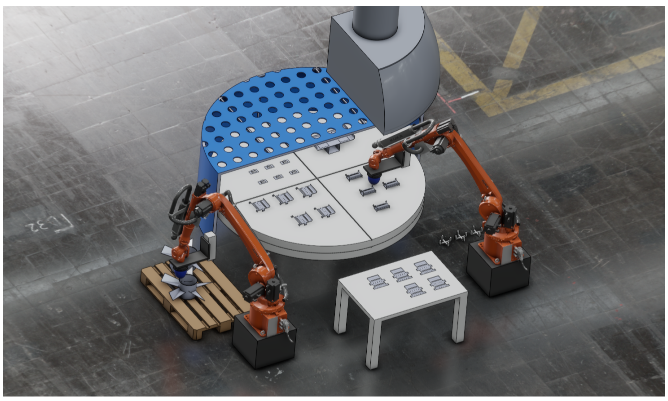

Fig. 1 Virtual setup of solution C in 3DEXPERIENCE.

The project is conducted in cooperation with a partner company. The partner company uses traditional sheet metal forming techniques such as: CO2 laser cutting, revolver punching, machine deburring, manual welding, and bending machines. However, the partner company has implemented robot welding, laser tube cutting, and an automated guided vehicle (AGV) as the newest technologies.

Six workpieces are designed by the group and are used as a baseline of workpieces, which lasers have to be able to manufacture. The workpieces are illustrated in Figure 2. The partner company has provided information regarding the time it takes for them to manufacture the workpieces and their associated sales prices. This is used as a baseline of what lasers have to compete against.

Implementation

An implementation is created in Dassaults 3DEXPERIENCE which is an umbrella program for a lot of Dassaults different applications. The implementation is of a solution for a laser cell, including robots and their controls.

2. State of the art analysis

The main findings of the state-of-the-art analysis are that of the following headlines.

2.1 Laser drilling

The laser type used for drilling is often a pulsed laser with highest possible frequency and power. The reason is, that a larger degree of the material is removed by vaporisation, instead of ejection of molt. This results in holes with a better precision and with a minimum of splatter around the holes. In comparison, both CW or pulsing lasers can be used for piercing. The reason is the low requirements regarding the quality of the holes, because the holes often are used for a subsequent cutting process. [2]

The penetration rate in drilling and piercing of the beam through the material can be estimated by Equation 1. [2]

$$v_{drill} = \frac{P_\delta \cdot \eta}{\rho \cdot (L_f + L_v + C_p(T_v - T_0))} \qquad \left[\frac{\mathrm{m}}{\mathrm{s}}\right] \tag{1}$$

2.2 Laser cutting

The maximum velocity for a laser cut can be approximated from Equation 2. The equation is from [3] and is based on thermodynamics and energy requirements. In the formula, the thermal efficiency is neglected, thus it is assumed that no thermal conduction occurs and that the molten material is removed immediately by the assisting gas. The enthalpy is the energy per mass needed to cause melting of the material being cut. [3] used $1.174 \cdot 10^6 \frac{\mathrm{J}}{\mathrm{kg}}$ as the entalphy in an example of cutting in steel. Thus this value is used as well. The velocity is used to give an indication of the time needed to cut sheet metal and to find the actual velocity physical experiments should be conducted.

$$v_{cut} = \frac{P \cdot \eta}{s_t \cdot 2 \cdot r_{beam} \cdot \rho \cdot \Delta h_m} \qquad \left[\frac{\mathrm{m}}{\mathrm{s}}\right] \tag{2}$$

2.3 Laser welding

From [2] a calculation of the maximum welding velocity is given. The calculation of the velocity is given in Equation 3. In this project, only the welding velocity is considered. Other parts of laser welding are neglected, because laser welding is combined with laser bending into a workstation.

$$v_{weld} = \frac{\beta \cdot P \cdot (1 - r_f)}{w_{weld} \cdot s_t \cdot \rho \cdot C_p \cdot T_m} \qquad \left[\frac{\mathrm{m}}{\mathrm{s}}\right] \tag{3}$$

2.4 Laser bending

The calculations of the bending are not an exact result but an estimation. A method described in [4] is to first calculate the velocity of the laser when bending with respect to laser diameter and then calculate the power to produce an incremental bend of maximum 1° per scan.

With the following equation, the scanning velocity, v_{bend}, can be calculated:

$$v_{bend} = \frac{a_{diff} \cdot d_B}{F_0 \cdot s_t^2} \qquad \left[\frac{\mathrm{m}}{\mathrm{s}}\right] \tag{4}$$

Where a is the thermal diffusivity can be calculated as:

$$a_{diff} = \frac{\kappa}{C_p \cdot \rho} \qquad \left[\frac{\mathrm{m}^2}{\mathrm{s}}\right] \tag{5}$$

Then the power, P, for the laser scan can be calculated. Before calculating the power, an incremental bending angle, θ_b, is chosen. The incremental bend must not exceed 1° . With this knowledge, the power can be calculated with the following equation:

$$P = \frac{\theta_b \cdot C_p \cdot \rho \cdot v_{bend} \cdot s_t^2}{3 \cdot \alpha_{th} \cdot \eta} \qquad [\mathrm{W}] \tag{6}$$

The cooling time t_c necessary in the bending process can be calculated by use of Equation 7. The cooling time calculated by the equation is for cases with active cooling, and without active cooling the cooling time is $\approx\ 5 \cdot t_c$. The calculation is based upon advice from supervisor. The cooling is necessary between each incremental bend of θ_b.

$$t_c = 4000 \cdot s_t + 3 \qquad [\text{s}] \tag{7}$$

2.5 Process Parameters

Process parameters and calculated process velocities for the four laser processes are given in Table I.

Process	Equation Used	Velocity	Required Power	Beam Diameter
Laser Cutting	Equation 2	$0.2652\ \frac{\text{m}}{\text{s}}$	2000 W	0.1 mm
Laser Drilling	Equation 1	$0.0011\ \frac{\text{m}}{\text{s}}$	2000 W	-
Laser Welding	Equation 3	$0.0745\ \frac{\text{m}}{\text{s}}$	600 W	0.04 mm
Laser Bending	Equation 4	$0.0135\ \frac{\text{m}}{\text{s}}$	270 W	4 mm

Tab. I Process velocities, power, and beam diameter.

2.6 Production at the industrial partner

The production at the industrial partner is a assumed to be in a line layout, where the parts are treated sequentially. The first process is laser cutting where the internal cuts are conducted before cutting the outside of the product. Then the workpieces are moved to the bending machine, where the bends are made in a semi-automatic bending machine. After bending the different parts of a product are welded together at the last station before packing the workpiece for transportation. The cost of production of the workpieces with this method is given in Table II and they are illustrated in Figure 2.

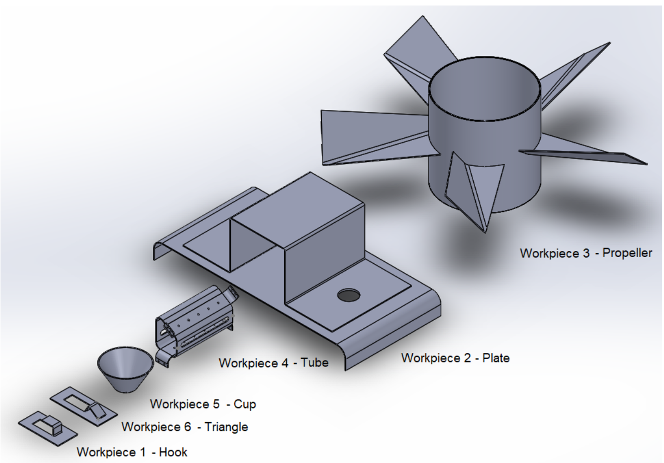

Fig. 2 The 6 benchmark workpieces. Workpiece 1 is 100 mm x 150 mm and Workpiece 3 is 530 mm x 530 mm. Workpiece 5 and 6 is not possible for the industrial partner to manufacture.

		Overhead	Programming laser cutter	Laser cutting and handling	Bending incl. setup	Welding incl. setup	Total time	Price
WP1	**1 piece**	1000 s	1200 s	1200 s	1200 s	x	4600 s	202 €
	5 pieces	200 s	240 s	360 s	300 s	x	1100 s	44 €
	100 pieces	10 s	12 s	24 s	66 s	x	112 s	5 €
WP2	**1 part**	1000 s	1800 s	1800 s	2400 s	1800 s	8800 s	326 €
	5 parts	200 s	360 s	720 s	660 s	1440 s	3200 s	111 €
	100 parts	10 s	18 s	54 s	192 s	1200 s	1474 s	53 €
WP3	**1 part**	1000 s	1800 s	1800 s	1500 s	7200 s	12900 s	781 €
	5 parts	200 s	360 s	900 s	720 s	5760 s	7940 s	274 €
	100 parts	10 s	18 s	72 s	246 s	4800 s	5146 s	140 €
WP4	**1 part**	1000 s	1800 s	1800 s	2700 s	2400 s	9700 s	331 €
	5 parts	200 s	360 s	720 s	850 s	1440 s	3390 s	102 €
	100 parts	10 s	18 s	54 s	198 s	1200 s	1480 s	41 €

Tab. II Estimated process times and prices from the industrial partner. The times and prices are per workpiece. WP is an abbreviation of workpiece.

3. Method

The method for developing a laser cell, capable of performing laser bending, cutting, drilling, and welding, takes offset in a revised version of the Modular Function Deployment (MFD) method.

3.1 Modular Function Deployment

Modular Function Deployment (MFD) is developed for generating of modular products. However, the method has been revised by [5] to generate modular manufacturing systems. In the method, required functions for the laser cell are divided into subfunctions. The subfunctions are afterwards combined into modules, based on their characteristics. Examples of characteristics are: Expected life time, service intervals, and technical evolution. Through a brainstorm, multiple concepts are generated for each module. Afterwards one concept is chosen for each module. The choosing is conducted by use of the Weighted Decision (WD) method. This resulted in the 12 modules listed in Table III.

Module	Description
Module 1	A QCW fibre laser from IPG
Module 2	A YLR/YLS fibre laser from IPG
Module 3	Two stationary hoods
Module 4	Laser process head from IPG with gas addons
Module 5	Existing laser process head technology for laser cutting
Module 6	Camera/scanner on the laser process head for measuring.
Module 7	A robot for transportation within the cell.
Module 8	A robot for loading and unloading and mirror controlled laser.
Module 9	A robot compatible with laser, fixture gripper and workpiece gripper.
Module 10	Fixation with small spikes below sheet metal.
Module 11	Product specific fixtures.
Module 12	Product specific fixtures.

Tab. III Description of the chosen concepts for each module.

3.2 Discrete event simulation

The discrete event simulation is used with data from the industrial partner. The software is developed by INCONTROL and is named Enterprise Dynamics 10.2 [6]. The program is used to establish an overview of a discrete production with the four workpieces, where possible bottlenecks can be analysed. Times provided by the industrial partner are given in Table II. The data foundation is done by the industrial partner where the estimation is based on manufacturing the six benchmark workpieces. Only four of the six workpieces is possible to manufacture at the industrial partner.

3.3 Simulation of production cell

By use of the revised version of the MFD and WD methods, a concept for each module is chosen. On this knowledge, four solutions of the production layouts of the laser manufacturing cell are generated. The four solutions are condensed to a single Solution C illustrated in Figure 3. This solution is set up to be simulated in 3DEXPERIENCE.

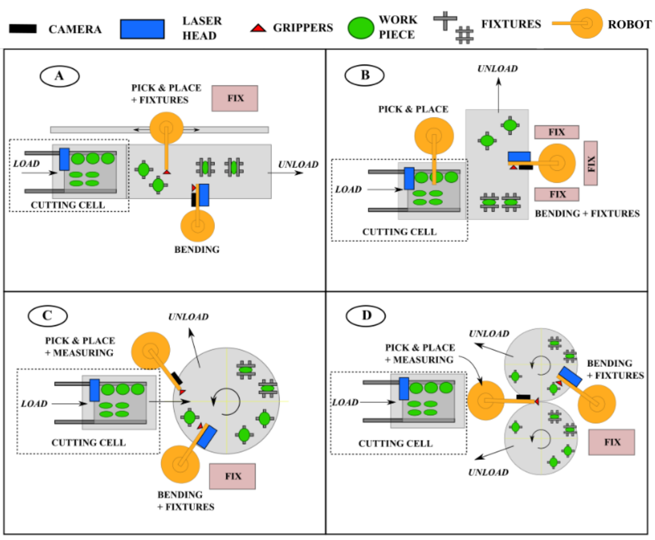

Fig. 3 Sketch of different concepts

The use of 3DEXPERIENCE is to create a simulated environment known as a digital twin. This implementation is conducted to determine which specific components are needed and how they should be positioned with respect to each other. Another advantage is to gather production data for the price calculations where the cycle time of the cell is an important factor of the total expenses. The implementation is illustrated in Figure 4 with an associated table in Table IV.

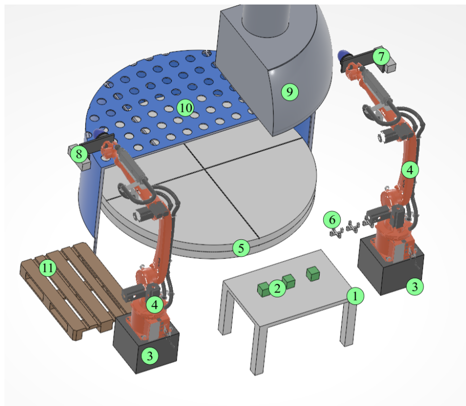

Fig. 4 Enumeration of products within the 3DEXPERIENCE Robot Simulation.

Number	Description	Product Type in 3DExperience	Comment
1	Table for loading	Stationary Product	Size: 1200x800x700 mm
2	3x Greybox workpieces	Manufacturing Product	Size: 100x100x100 mm
3	2x Robot elevator	Stationary Product	Size: 500x500x400 mm
4	2x KUKA Robot KR16	Robot (Imported)	6-Axes R2010
5	Rotary table	Tool Equipment	Size: 2400x2400x850 mm
6	3x Greybox fixtures	Manufacturing Product	Size: 150x150x50 mm
7	Weld/bend process head and Gripper	Tool Equipment	Greybox design
8	Gripper and camera	Tool Equipment	Greybox design
9	Exhaust hood	Stationary Product	Self-designed, 1500 mm above rotary table*
10	Nozzle grid for active cooling	Stationary Product	For active cooling**
11	Pallet for unloading	Stationary Product	Size: 1200x800x144 mm

Tab. IV Table of included products in the 3DEXPERIENCE simulation. *Hood is placed 1500 mm above the welding area based upon [7]. **Implemented if active cooling is a necessity in a later design. Depends on the operations of the cell if active cooling is necessary.

3.4 Prices calculation

A modern production is based on economics. To gather the right data to base a price estimation on the complete cell, is a large and time consuming task. The process is necessary to get knowledge about, if the workpieces produced can generate a profit. The method used is to gather as much data as possible to gain the insight. It is difficult to have the complete insight in prices, production and workflow. The assumptions make it possible to know where the calculations are only a rough estimate but makes it possible to create the estimation.

The price estimation is based on the following list of expenses:

- Investments in equipment to the laser cell
- Variable expenses as gasses, electricity, workforce ect.
- Production time estimation for each workpiece
- Profit for each product and break even time for the cell

With the following knowledge a decision on if the risk of investment is at a level our industrial partner can carry, and earn an acceptable return of investment can be taken.

3.5 Value stream mapping

A value stream map (VSM) is made to highlight the different processes of the laser manufacturing cell. The process times inserted into the VSM are those of workpiece 4 - Tube, when produced in a batch size of 20. The VSM is a tool that can be used to reduce waste and increase efficiency by mapping out the relation between different processes in a production. VSM is associated with LEAN production where the goal is to minimise waste within the production setup. Waste is defined as the difference between the value adding and non value adding process times.

4. Results

4.1 Discreet event simulation

The strongest driver to the cycle time is the welding process. The utilisation on the three stations when producing 100 of all four workpieces is:

- Cutting station: 2.6%
- Bending station: 9.6%
- Welding station: 98.8%

This shows that the slow welding station controls the overall cycle time and if this bottleneck can be reduced, the overall cycle time would be reduced from this. If other process times are slowed down, the overall cycle time is only affected if the welding process is no longer the longest. Note that workpiece 1 does not have any welding.

This combined with the low utilisation of equipment emphasises the need for a production setup capable of producing low volume/high variety parts, which can reduce the price of such parts.

4.2 Simulation of production cell

Used Results

- Positioning of products such as the robots and determining the size of the supports that elevate them. This is conducted so that the robots have a bigger work area on the surface of the table, instead of having maximum reach e.g. underneath the rotary table.
- Selection of robots to fit their respective functions. The two robots in the solution are chosen to be of the type KUKA KR16 R2010. The robot type is the same, because their workspaces are equally sized, namely the size of one quadrant on the rotary table.
- Estimating times for robot kinematics related to loading and unloading of workpieces onto the rotary table.

Areas of improvement

- The size and positioning of the robots. This is to optimise the speed of the robot, by utilising that robots moves faster along the periphery of their reach.
- Include additional grippers and fixtures with designated places on racks. This could result in the possibility of choosing a smaller and cheaper robot because of removing the need for picking such from the floor.
- Design of an extraction system where collision prevention is incorporated.
- Design of a cooling system with sufficient cooling and where collision prevention is incorporated.

If the sequencing of the robot movements in the virtual setup is realised, then it is possible to test different production scenarios with different manufactured workpieces. The following list of objectives could have been used to evaluate the operations of the working cell.

- Further understanding of process steps and their variety depending on the different workpieces.
- Estimate utilisation and production capabilities of the chosen equipment in a given configuration.
- Locate areas of improvement in the operations of the concept by e.g. locating bottlenecks.
- Determine if the concept can benefit from manual labour by lowering the degree of automation e.g. by loading and unloading manually instead of having a robot for this.

4.3 Prices Calculation

The assumptions about assisting gas and manual labour are regarded reasonable. The assumption for the power usage for the manipulators is regarded conservative, and the real power consumption is therefore expected to be lower. The assumption about the lasers usage of power is regarded optimistic, and the real power consumption of the lasers is expected to be higher.

Based on Figure 5, it can be concluded that workpiece 3, the propeller, is the workpiece with the highest profit. Common for the workpieces is that the profit per workpiece is decreasing with an increase in workpieces manufactured. However, it should be noticed, that the profit is per workpiece. The values on the 2.-axis should therefore be multiplied with the values on the 1.-axis to determine the profit of a batch. The profit is calculated by use of the sales prices given in Figure 6 and the expenses per workpiece. The profit per workpiece is given in Figure 5.

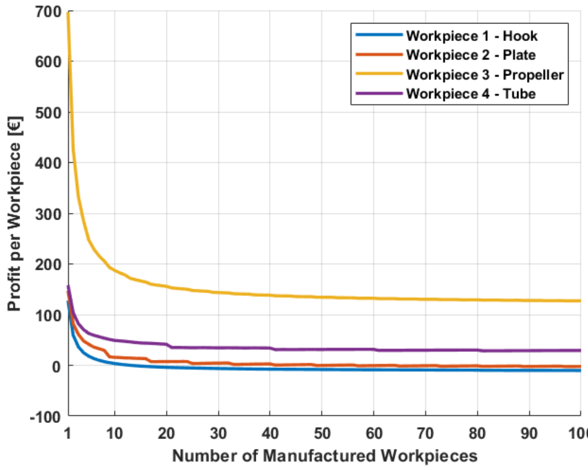

Fig. 5 Plot of profit per workpiece versus number of manufactured workpieces.

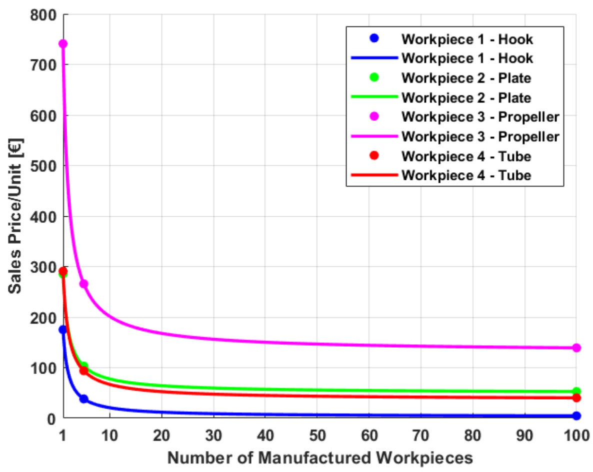

Fig. 6 Interpolation of the quantity versus new unit price using the power method.

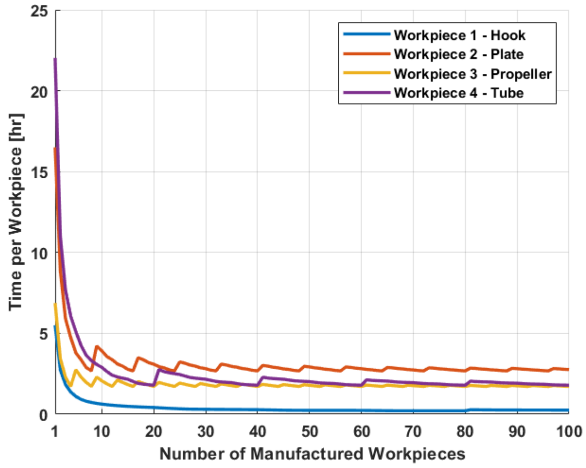

Fig. 7 Laser bending process time per workpiece, with respect to the number of workpieces manufactured.

The payback time is when the profit from manufacturing workpieces exceeds the initial investment. The calculations are based on two cases: One where the cutting/drilling workstation needs to be bought, and one where it is already implemented in the production facility. These are listed below. The payback time is calculated by Equation 8 and 9.

$$\text{Payback time} = \frac{\text{Initial Investment}}{\text{Profit per Year}} \tag{8}$$

$$\text{Profit per year} = \frac{\text{Uptime of laser cell per year}}{\text{Time per batch}} \cdot \text{Profit per batch} \tag{9}$$

When calculating the payback time for the initial investments, a set of assumptions are used.

- Workpiece 3 - Propeller is chosen for the calculations. The choice is made, because it has the largest profit. However, it is not expected, that the laser cell is paid back by only manufacturing propellers. Instead, it is assumed that workpieces with similar characteristics are manufactured.
- The calculations are based on a batch size of 20 workpieces. The size is regarded sufficient for representing prototypes and small batch manufacturing.
- It is assumed that there are always orders of workpieces. Meaning, that there is always workpieces to be manufactured.
- It is assumed that the laser cell is running 24 hr per day, 200 days per year. However, in a real

setting an unknown duration of downtime needs to be accounted for.

The payback time of the investment of the laser cell is listed in Table V.

Laser cell with CD workst.	Initial investment	Payback time	Number of batches
Already implemented	428 000 €	1 year + 1 month	≈ 138
To be bought	1 503 000 €	3 years + 9 months	≈ 483

Tab. V Initial investments, payback times, and number of manufactured batches required for the payback time. When the cutting/drilling workstation is already implemented, and when it needs to be bought.

4.4 Value stream mapping

The VSM illustrates the flow of goods and information between different stakeholders. The production control is the main stakeholder that conducts the production in the given VSM. A series of abbreviations have been used alongside standardised VSM symbols. The abbrevations used are the following illustrated in Figure 8 on the following page. [8]
C = Cycle time
S = Setup and programming
U = Utilisation
A = Available hours per day
FR = Fail rate

It can be concluded from the VSM cycle time of 7702 s and the process time of 4632 s that there are some extent of non value adding processes that are not balanced. The difference between the cycle time and the process time is 3070 s. The three main non value contributions are from the setup and programming of the laser cell and the setup of the fixtures for the welding and bending which both are assumed to be 10 min for each of these processes.

5. Conclusion

Based on the methods for concept generation, a solution which fulfils the required functions is developed. The chosen solution is Solution C and it is further developed in 3DEXPERIENCE, where considerations about the components are conducted when creating the virtual setup. However, the virtual setup was not completed, and a functional virtual setup is therefore not developed yet. If this is developed, further analysis of the solution chosen could be conducted.

The economic considerations are focusing on the payback times, if the cutting/drilling workstation is already implemented in a production facility or is to be bought by a company. The payback times for the two cases are calculated to be 13 and 45 months, respectively. However, the payback times are not regarded realistic, due to the associated assumptions. It is expected that the payback times are longer in a real setting. For future work, a more complete business plan could be created, containing balances, expected yearly results, and depreciation.

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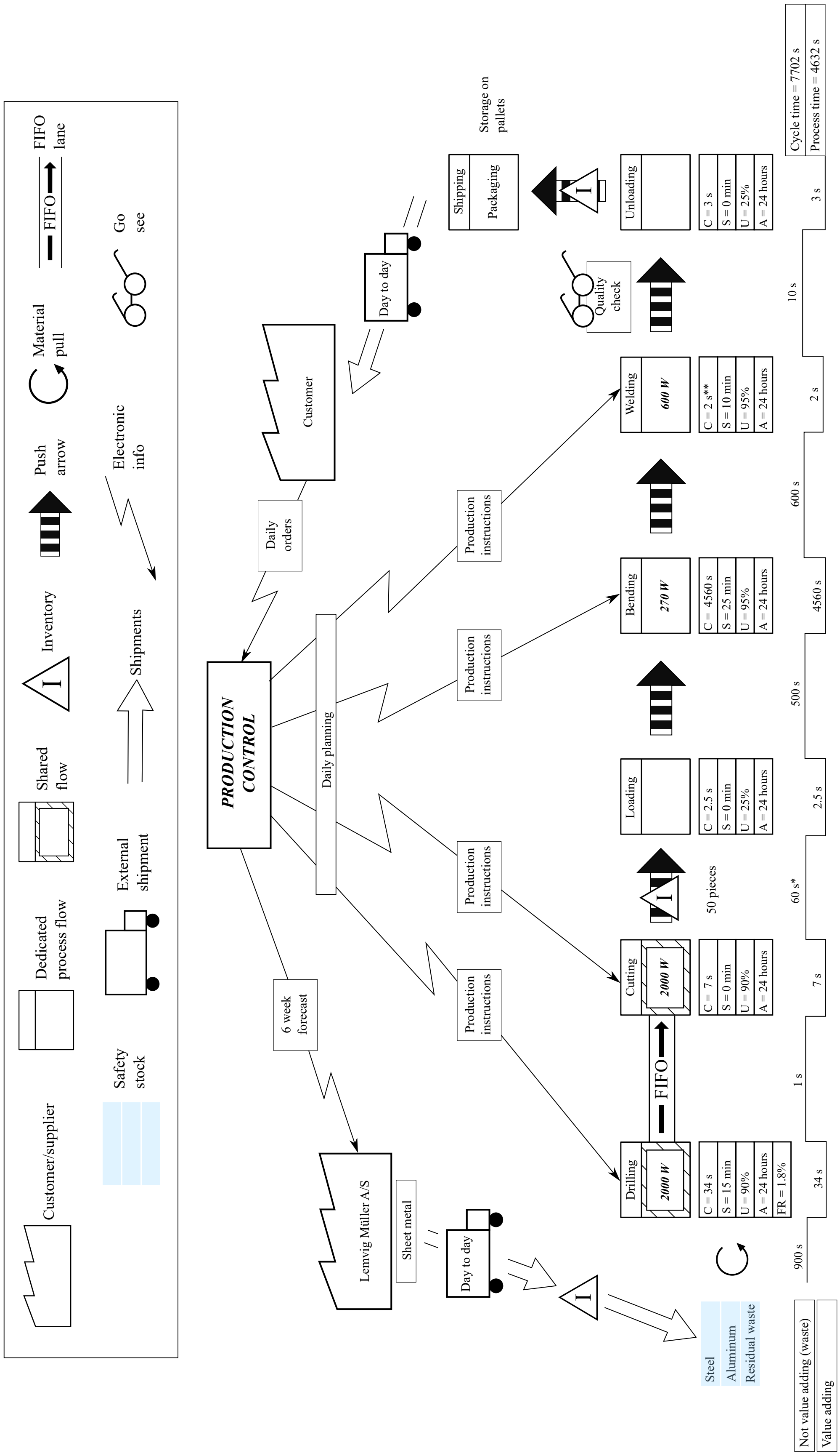

Fig. 8 Value Stream Map of the laser manufacturing cell. The processes are set up based upon the manufacturing of workpiece 4 in a batch of 20.