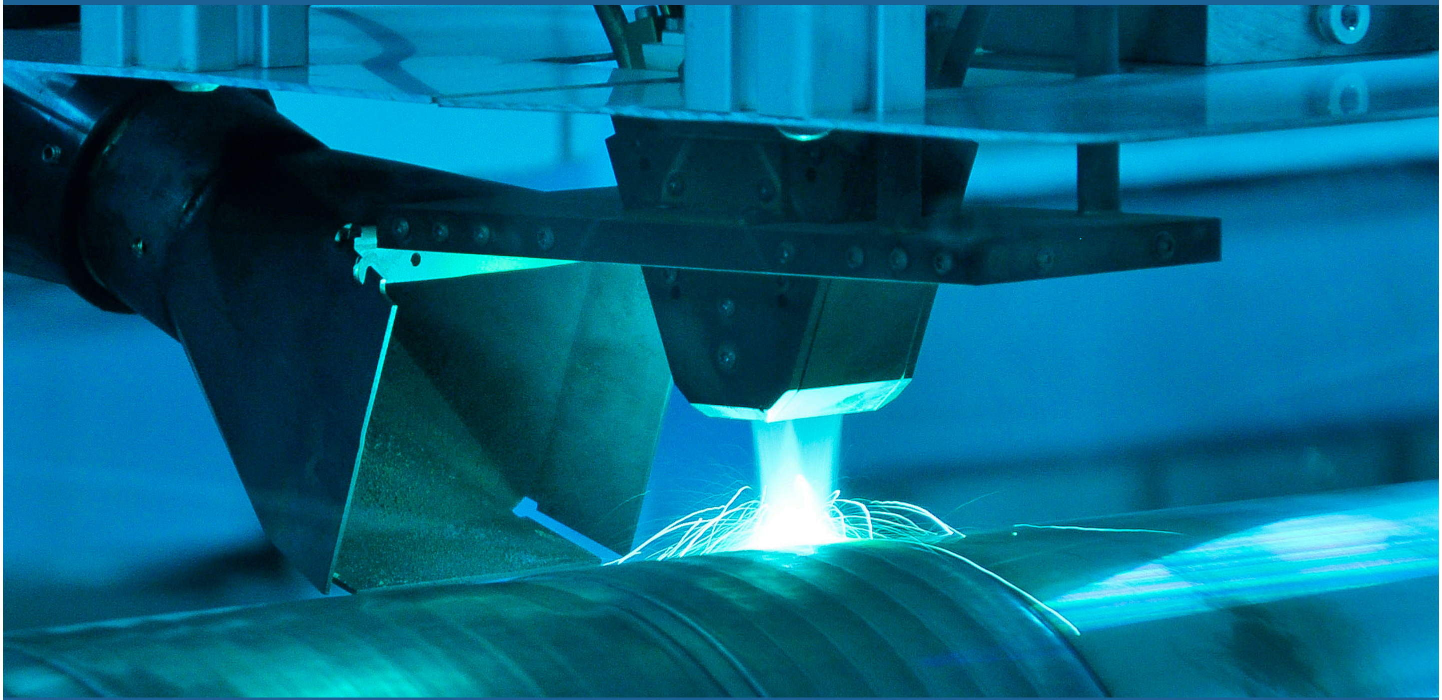
UNIVERSITY OF TWENTE. VHT VAN HALTEREN TECHNOLOGIES

MSc Thesis



Dashboards for increased insight into laser cladding

Advancing data collection and visualisation to increase insight into the laser cladding process at Van Halteren Technologies

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Emerging Technology Design
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Chapters

"We want to create an interface that is simple for the operators but has enough depth and information to increase insight into the laser cladding process here at van Halteren Technologies Boxtel" - The process engineer

Content

Abstract

This thesis was conducted at van Halteren Technologies Boxtel, where laser cladding errors during production are causing excessive costs. Two directions were found to reduce these costs. Direction one is about improving operator knowledge, training and procedures. The second direction is about improving data collection/visualisation and enhancing process insight. The second option was chosen as a subject for this thesis. The laser cladding process was analysed, and the key indicators of an exemplary process were found. It was noticed that a clear overview of all process data was missing and not displayed correctly to stakeholders. The same goes for data resulting from quality control. Data streams were coupled and stored in a new database to make this readily available. From here, informational (live) dashboards were built to display historical and live data. In the live dashboard, 'traffic light ' indicators were included with logic behind them to communicate the process's current state. This helped van Halteren create a better and faster insight into their process and quality data and is helping to spot quality-affecting factors quicker during production by the operator. After production, it helps the process engineer analyse data in a fraction of the time it took before, increasing the likelihood of finding causes of problems and quality variations.

€117k costs

When unexpected problems arise during the cladding process, this can cause large problems for production. The "Non Conformance Reports" of rods that need a remake can increase the costs by as much as €7.000 per rod. This year, the costs caused by problems relating to the coating process are €117k, keep in mind that some of the costs were caused by faults in the base material.

Abbreviations

ANN	-	*Artificial Neural Network*
AR	-	*Augmented Reality*
B2B	-	*Business to Business*
CNN	-	*Conventional Neural Networks*
DOE	-	*Design of Experiments*
EHLA	-	*Extreme High Speed Laser Application*
EMAqS	-	*Name of Fraunhofer camera, no known abbreviation*
GUI	-	*Graphical User Interface*
HMI	-	*Human Machine Interface*
IETM	-	*Interactive Electronic Technical Manual*
IOT	-	*Internet Of Things*
KPI's	-	*Key Performance Indicators*
LC	-	*Laser Cladding*
LCL	-	*Lower Control Level*
LLM	-	*Large Language Model*
MA	-	*Maintenance*
NCR	-	*Non-Conformity Report*
NIR	-	*Near Infrared (Camera)*
OP	-	*Operator*
PE	-	*Process engineer*
UCL	-	*Upper Control Level*
VH	-	*van Halteren*
VHT	-	*van Halteren Technologies*
VHTB	-	*van Halteren Technologies Boxtel*
WPS	-	*Welding Procedure Specification*

01

Introduction

van Halteren Technologies

Van Halteren Technologies (VHT), previously Hydraudyne, is a Dutch company founded in 1954 with multiple locations throughout the Netherlands: Boxtel, Bunschoten, and Zwolle. VHT is a leading technology provider specializing in the design, production, and supply of a wide range of electromechanical and hydraulic products, serving industrial customers and governments worldwide. This thesis was conducted at the Boxtel location. The company's core expertise has traditionally been in engineering, manufacturing, and overhauling cylinders, actuators, and power units. However, in recent years, the company has expanded its operations to include the assembly of disconnectors and the refurbishment of defence vehicles. These activities are conducted within the company's operations department, which oversees the factory at VHT Boxtel. This department employs 135 professionals who work to maintain the high standards of quality and reliability that VHT Boxtel is known for. VHT Boxtel exclusively serves the B2B market, focusing on delivering high-quality technological solutions to business customers. The customer base includes both industrial entities and government agencies around the globe. Through its commitment to excellence and innovation, VHT Boxtel has built a strong reputation as a reliable supplier of advanced technological solutions. The hydraulic cylinders van Halteren produces end up in large infrastructures such as dams, bridges, or launch pads. During cylinder production and overhauling, the rods must be provided with a durable, wear-resistant, and anti-corrosive coating. Constructing the entire rod out of non-corrosive material is too expensive or structurally impossible. Therefore, coatings are applied to the rods surface, for example, using laser cladding, which is the focus of this thesis.

A hydraulic cylinder consists of several key components, each playing a vital role in its operation. The rod is the part that moves in and out of the cylinder, driven by hydraulic pressure. Attached to the rod is the piston, which separates the internal chambers of the cylinder. The rod eye, located at the end of the rod, connects the cylinder to the mechanism it powers. Surrounding the piston are piston seals that prevent hydraulic fluid from leaking between chambers. This makes it essential that the rod's surface stays smooth and without rust or corrosion, hence the coatings. The tube, or cylinder barrel, houses the piston and rod, with the tube end serving as a closure. Together, these components ensure the efficient transfer of hydraulic force to perform heavy-duty operations.

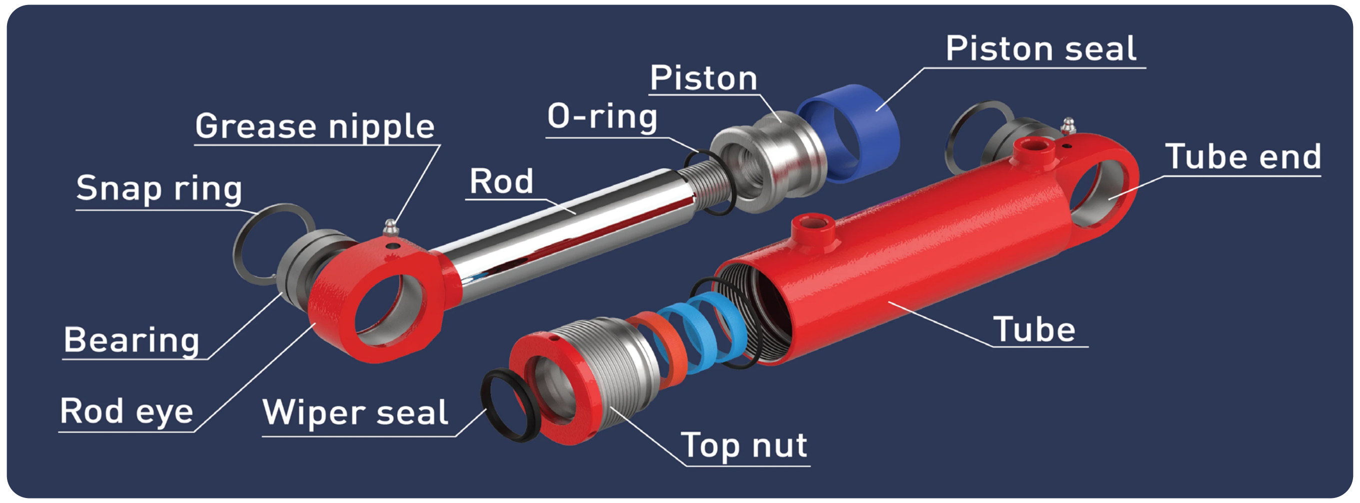


Figure 1 - Anatomy of a cylinder [68]

Laser cladding at VHT

An essential step in the overhauling and production of cylinders is the application of a coating to the rods of the cylinder. These cylinders start their path in the company as large steel rods. These rods are welded together to obtain the required piston rod length. They are then machined and honed to be cylindrical and straight, this is the last step before the coating is applied. After honing, a coating of approximately 1.5 mm is applied using laser cladding. This rough layer will be honed and polished to create a smooth, corrosion-resistant layer on the outer surface of the rod. The surface needs to have a specific smooth texture to create the correct interface with the seals (explained at page 28). The machine that is used for this process was manufactured by the German company Fraunhofer. This is more of a research institute than a machine manufacturer. However, they still provide support and maintenance for the machine, so they are still essential stakeholders. A cladding machine has many variables and settings that make it a complex process for the operator to monitor and manage. In addition, sensors and cameras must provide insight into the process; therefore, this insight is limited to the number, type, and accuracy of the sensors within the Laser Cladding setup. However, the machine has not been as stable as is preferred, and needed during production. Therefore, improvements can be made in this area to ensure that the cladding process is more stable and reliable. The operator should obtain a complete and clear insight into how the machine is performing. Apart from the operator, maintenance should also be up-to-date with the state and performance of the machine to be able to perform their work correctly and keep the machine in operating conditions. Lastly, a process engineer should be able to oversee the laser cladding process and the operators working with the machine.

Problem statement

During the first few weeks at van Halteren, the exact assignment of this thesis still needed to be specified. By walking along with the development engineer, production engineer, quality control and operators, an overview of the challenges VHT faces with regard to laser cladding was formed. This will be discussed in this section.

The laser cladding process at van Halteren is a key step in the production of cylinders. However, this process does not always go as smoothly as is preferred. This has multiple causes, such as hardware malfunctions, material quality problems, incorrect calibrations and settings, or problems with monitoring of the process. Also, the causes are not always as apparent; they can be found way later in production and can be caused by a combination of circumstances. Using a proven recipe with a slightly worn nozzle and an older type of steel can cause the process's results to vary unexpectedly. The amount of parameters and outside influences, inherent to the process, make problems more likely to occur. These problems include human errors in maintenance or the setup of the machine. Finding these problems in time and acting when necessary is essential and this detection will increase if the process engineer, operators, and, indirectly, maintenance have the tools to do so. Operators should have enough knowledge to run the machine and get understandable and usable feedback from the machine. This makes the interface between the machine and the operator essential in producing without errors. The working instructions available, the training, and the information the operators can access are vital to improving the machine's functionality. Currently, there are few instructions and guidelines for (new) operators. For process monitoring, the operators have multiple screens, with different systems displayed. The screens are filled with parameters and programs, and the operators have to control the process and monitor the machine mostly on experience without a guide.

> *“We want to prevent quality issues before they occur.”*

The process state should become clear from the operators' interface to help them monitor and gain more insight into the process's state. Earlier ideas surrounding the monitoring and control process focussed on making a step-by-step plan for the operators on what to do when standing in front of the machine. This is a very static list and is made so that anyone standing behind the machine can follow it without thinking. The dynamics of this complex machine make it so that this method may not work optimally for this machine. In this way, operators are not promoted to think for themselves about the results of their actions, or lack of the actions taken by them. Another vital party that interacts with the machine is the process engineer. It is his task to arrange everything for coating and give the right tools to the operator. The process engineer has the most indepth knowledge of the process. However, this knowledge is with this person and is not documented well. It would be helpful to have this knowledge documented and accessible for future situations. Also, experiences in solving problems that occur can be forgotten. A way to build knowledge surrounding the process and document this for later implementation needs to be included in the current workflow.

In conclusion, there is a clear need to enhance the interaction between the operator, process engineer, maintainer, and machine. This can be achieved through the development of tools. One such tool could be designed to provide (new) operators with a deeper understanding of the machine's operation, thereby improving their ability to recognize faults and solve problems. This approach will not only increase their involvement in the process but also their control over the machine. The process engineer does not continuously interact with the machine as the operator does; they also get indirect information about the machine from the operator. This makes the interaction between the operator and the process engineer important. It would be helpful for both parties to know when and what to notify each other. This would increase their knowledge about the state of the machine and the laser cladding process, helping it to run with fewer hiccups and faults. Making data more accessible and adding a clear way of data visualisation will also aid in increasing the operator's insight.
Last year the NCR's amounted to a total of 117k, which is much higher than the other processes. However a fault in laser cladding automatically results in high reworking costs on comparison to a lathe at VHT.

Two ways forward

From the problem statement and observations made at van Halteren, multiple ideas emerged about how to resolve the issues and improve the process. These ideas could be divided into two separate directions: the first direction involved improving operator training, communication, fault logging, and procedures; the second direction involved improving data collection and visualisation to increase insight and knowledge about the process. The research done on the first direction focused on the operators' training and information access, as a complete training course is unavailable. Human errors have had significant consequences at VHT, so better training could help reduce them. It could also help train new operators, giving them a solid knowledge base. Research, ideas, and proposals done in this first direction have been added as an additional section in the appendix. Some overlapping sections of research from the first direction can still be found in human interaction research because it also applies to the chosen goal of this thesis. The remaining work is added to the end of the thesis for clarity and to create an additional starting point for future research or work on the training aspect.

The second direction was chosen as it is the more technical option and delves deeper into the cladding process. Before a tool that assists with logging and passing on knowledge about faults, experiences, and process information can be developed, it is crucial to gather these insights first. A better interface and data collection system will play a pivotal role in making the process of gathering these insights more efficient and effective.

BHAG - Big Hairy Audacious Goal

To know what next step to take in stabilizing and improving laser cladding at van Halteren, it is essential to have a vision of the ideal situation. This ideal can be described as a Big Hairy Audacious Goal, an inspiring and daunting goal that usually takes more than ten years to complete. Therefore, The step that will be taken during this theis will be in the direction of the bigger goal VHT wants to achieve. In the case of this thesis, the product, academic research, and resulting methodology to replicate such solutions will have a time restriction of 8 to 9 months. Therefore, the first solution and step to take in the BHAG's direction will need to fit within those few months. This means that the goal described here will not be accomplished during this thesis as this is a goal for the next ten years. However, this goal is used to begin setting up the infrastructure to achieve this goal in the future. This thesis will be the first step toward this goal, offering a promising path for the future. After conducting extensive research into new technologies that could enhance the production process and engaging in insightful discussions with the operators, process engineers, and other stakeholders, this BHAG has been collaboratively formulated.

In ten years, the machine will be able to produce in three shifts during the week, with operators who only have to worry about placing the correct rod inside the machine, clamping it well, and pressing start for that recipe. During cladding, VHT can monitor multiple machines at a time, if needed, because the system has enough sensing and control built in to keep the process steady and warn the operator when needed. The NCR costs of the machine have been reduced drastically as there is a more profound understanding of the process and a more preventative approach to possible errors in every specific recipe.

To reach this goal, multiple upgrades and changes must be made at different levels. These will be changes in the technology used, as well as improved interaction, training, and information flow. Because it was found that the interface of the machine and the lack of clear information contribute to a large part of the faults that happened, in an ideal situation, new technologies are used for better monitoring, automation and fault detection. A straightforward interface is to be used so the operators have a complete view of what is happening. Also, the operators are trained well and have a place to look up information when needed. Lastly, the information that is learned about the machine is communicated, documented, and used for the training of operators and ANNs, which will be able to monitor the process automatically.

Technology

New sensors and cameras are coming to the market any day, including software to automatically monitor and adjust specific parameters when needed. Using new sensors and controlling software, the LC machine is so stable that it only has to compensate for differences in process parameters that the rod and powder bring into the process. An excellent example of this are changes in the reflectivity of the surface caused by machining differences, differences in powders and materials, and the geometry and bending of the rods. If the process is stable and can automatically be adjusted (e.g., laser power) for the parameters, it cannot control fewer hiccups will occur. The new control system, in combination with ANNs, will identify changes in the process and update the settings in real time, multiple times per second, constantly maintaining optimal process parameters. Also, it will give operators enough information to ensure the process is performing as expected. These operators can now manage multiple machines because they can be remotely viewed, and possible faults are automatically detected.

Interaction

There should be a much more straightforward and more understandable interface for the operator with essential information that is up-to-date and needed in monitoring of the process. This means grouping relevant parameters and using different graph time scales to notice quick changes. However, there can also be very subtle changes over the hours needed for a rod's cladding, as small changes during the long coating process can already indicate problems.
Colour coding is used to direct attention to values deviating from normal and help group parameters that fit together. The machine's dashboard will ask for calibration values and automatically implement this in the interface, ensuring that these steps cannot be skipped and are done quickly. With this new interface, operators can be confident that if no warnings are showing, the resulting layer is optimal. If warnings are showing, it should indicate possible problems and there should be a guide for the operators on what to do in specific situations. The operators should, if a problem is identified, be able to solve the problem themselves, ensuring a sense of security and confidence in the reliability of the system. The ANN can control the process's input parameters to increase the success rate. It will notify operators if it thinks specific values are deviating from normal. At this moment, operators do not change parameters during production, so for them, only the reliability and usability of the machine will increase without removing tasks.

Training

There will be a complete training program for new and experienced operators. New operators should be able to walk alongside experienced operators and use the available training tools for support with learning. This learning tool should be visual and replicate the environment of the machine. The information should be taught during operation and be able to be looked up during operation. The different parts of the machine should have, for example, QR codes that bring the operators to the right chapter or part of the training that teaches about this part/procedure. The training must be complete and simple so the job can be taught only using that tool. However, to build confidence and experience, there will always be an experienced operator helping in the beginning. This tool should make use of the newest and best training methods and technologies to do so. This can include interactive web pages and even a complete AR training. Lastly, it includes an option to easily add information and expand the training.

Information flow

The logistics and information flow surrounding the process will be streamlined and automated. This means that from making the recipe for a particular rod to the cladding process, no information should be manually taken over from one place to another. The rod can be input into the machine and scanned, then the recipe is automatically loaded, and all the machine parameters are set correctly. The interface will also be updated to show how much certain values may deviate and what is essential to look for with this recipe.

Translation to goal thesis

The step that will make the most impact and is the most influential in reaching the set goal will need to be identified. Also, there should be a start with laying down some foundations for future technologies and new technologies that are already available should be implemented.

The training aspect and the machine interface are the main things that need improvement to reach the set goal. To finish the goal and document this process in the given eight months, one focus point needs to be picked to start with. The machine and its errors should first be thoroughly understood and a way of identifying problems quickly should be available to create a training that includes information on how to do so. That's why it is helpful to tackle the interface of the machine first. Start gathering more helpful information about the process and find out how to communicate this to the operator, and store it for analysing and training of the ANN's. This is why this thesis will aim to optimize the HMI by creating informational dashboards and better insight. The outcome of this BHAG was used to set a general development direction from which the idea of creating better dashboards was born.

For now, some capabilities that can be added, like a live stream in the dashboard, are unnecessary, however they are all steps toward the ideal of pressing start and monitoring the machine remotely .

The goal of the thesis

To help gather these new insights, ways will be looked at to improve the collection, storage, and visualisation of all the data that is currently collected and can potentially be collected about the LC process. Afterwards, this data should be able to improve the process and its stability. The goal is to create a better interface that clearly communicates the sensors and process data to the operator and the process engineer. The developed interfaces should help VHT spot and act on problems. Research should be done to learn how to tackle the creation of these interfaces and learn more about what is important in the laser cladding process. The research and the process of creating these interfaces can also be of interest to other companies.

The research goal of this thesis is to answer the following main research question and the corresponding sub-questions through literature research and the experience gathered by implementing a better data interface at van Halteren Technologies.

02

Research questions

Main research question

How can improved data logging and real-time visualization aid in improving process stability and product quality?

Sub questions

1. *What defines an excellent quality cladding process and resulting layer?*
2. *Can unifying relevant process data into a clear visual interface help operators and process engineers create coatings with fewer quality problems?*
3. *What new technologies and hardware can give more insight into the process?*
4. *Can ANNs be integrated into an HMI to aid in detection and monitoring?*
5. *How can live information and the state of the process be displayed?*
6. *How to couple the quality output to process logs and live data to help improve quality during production?*
7. *What are the technical challenges and possibilities in setting up this new interface?*
8. *What is important in the design of the operators' interface?*

These questions will be answered following a literature review and by implementing the new interfaces at VHT. The literature review will focus on the human aspect, the theoretical aspect of laser cladding and the data visualisation aspect. To learn from the implementation of the dashboard and to deliver a better product, feedback will be gathered on the use of these dashboards and the usability of the new data. With this feedback, there can be figured out if insight into the process is improved and if this results in a better coating.

Research Methodology

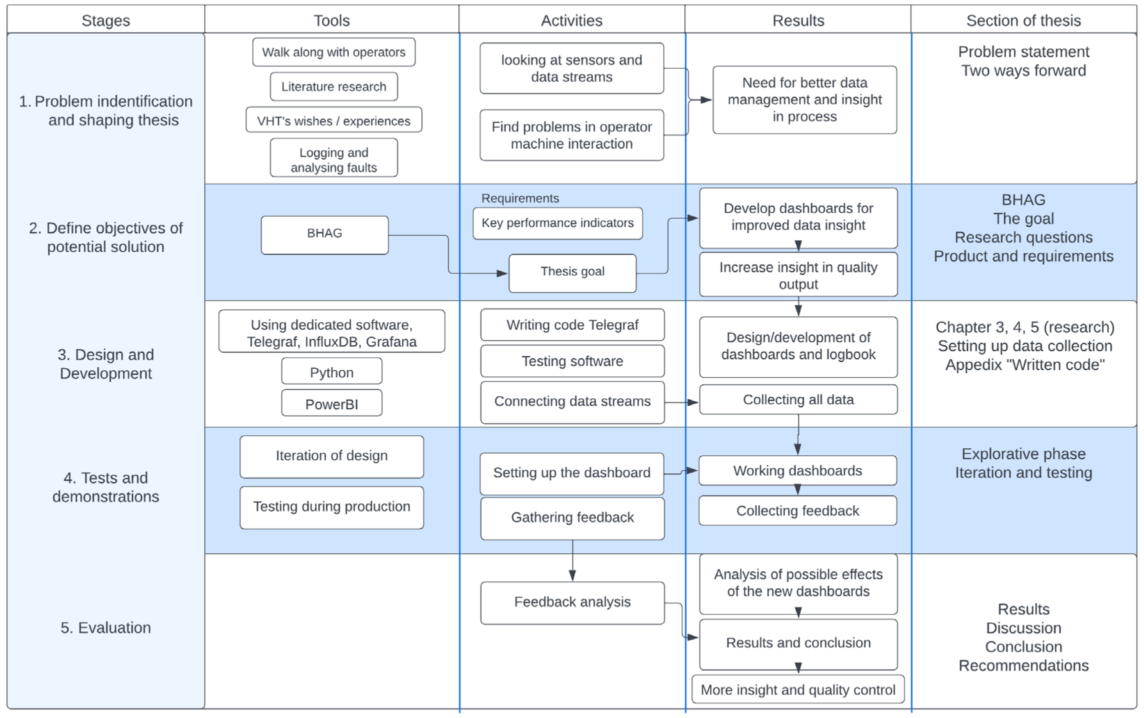


Figure 2 - Research methodology

The thesis methodology is structured into five distinct phases, each focusing on progressively refining the research and development of a solution to improve data management and operator-machine interaction at VHT. See Figure 2 for the tools, activities and results of each phase. Figure 3 gives a idea about the flow of the thesis.

1. **Problem Identification and Shaping the Thesis**
This phase centers on recognizing the core issue, which is the need for better data management and insight into the interaction between operators and machines.
2. **Define Objectives of Potential Solution**
In this phase, specific objectives are set, such as developing dashboards for better data insight and management. Key performance indicators (KPIs) are identified to guide the design of the solution.
3. **Design and Development**
Here, the technical solution begins to take shape. Activities include writing code, testing software, and connecting data streams. Dashboards and logbooks are developed to visualize and track real-time data.
4. **Tests and Demonstrations**
The fourth phase involves collecting data, setting up dashboards, and gathering feedback from users to refine the design. The system undergoes iterative testing, allowing to address any issues and optimize the system for real-world use.
5. **Evaluation**
The final phase focuses on analysing the effects of the new dashboards on operational performance. Feedback is incorporated, and there is evaluated whether the objectives set in earlier stages were met. The thesis ends with conclusions and recommendations for future improvements.

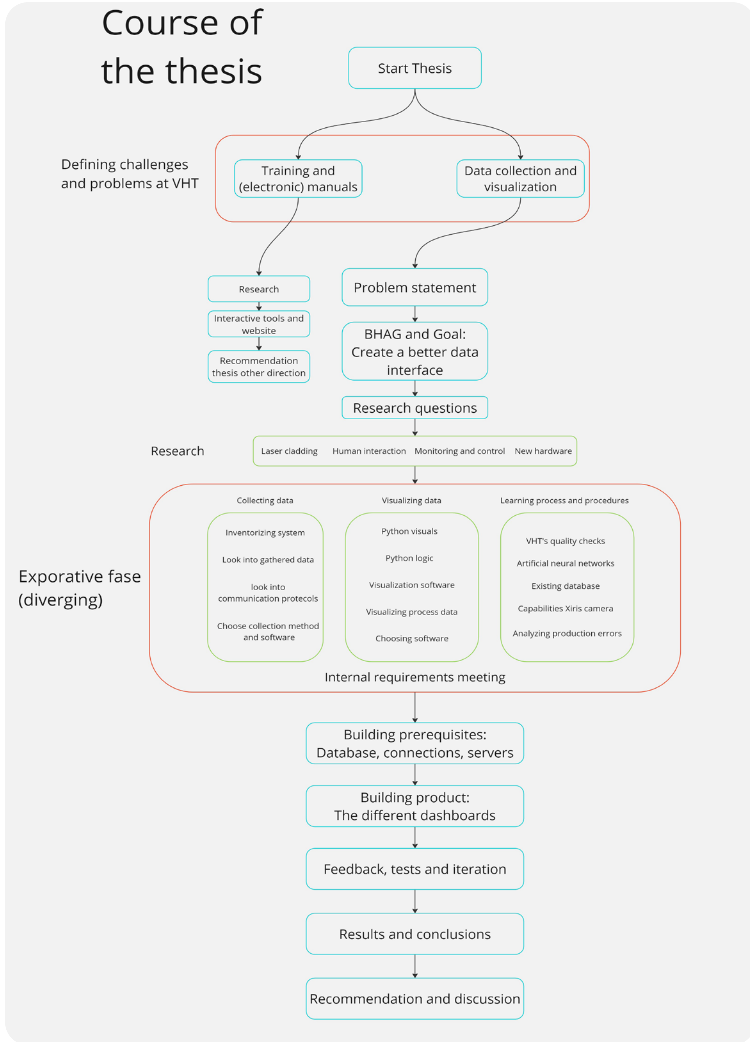


Figure 3 - Cource and flow of the thesis

03

Process Research

Introduction to laser cladding

The method of laser cladding is used as a hard-facing process [1]. This is the application of a material that is more corrosion and wear-resistant onto the surface of a component by using thermal spraying, welding or, in the case of van Halteren laser cladding [2]. Laser cladding has some advantages, mainly its lower dilution rate, small heat-affected zone and good metallurgic bonding [3]. Laser cladding that uses powder injection is superior to other methods, such as paste feeding, wire feeding, or pre-placed powder. This is why it is a method that has been found to be good for practical use; it has better energy efficiency, control, and reproducibility [1]. The laser is a very controllable way of heating the powder and substrate. Because of this, it has found widespread use for the protection of materials against corrosion and wear. Van Halteren uses the cladding process to coat the steel rods for large hydraulic cylinders; these should be resistant to wear over the years and corrosion from, for example, splashing sea water over the rods of a water barrier cylinder. By coating the rods with a protective layer, the bulk of the material does not have to be made from this more expensive corrosion-resistant material, and the mechanical properties of the bulk material are still used without having to change this material to the non-corrosive material. So, this method uses the corrosion resistance of the outer layer and the strength and cheaper costs of the bulk material. Figure 4 gives a schematic overview of a standard laser cladding process.

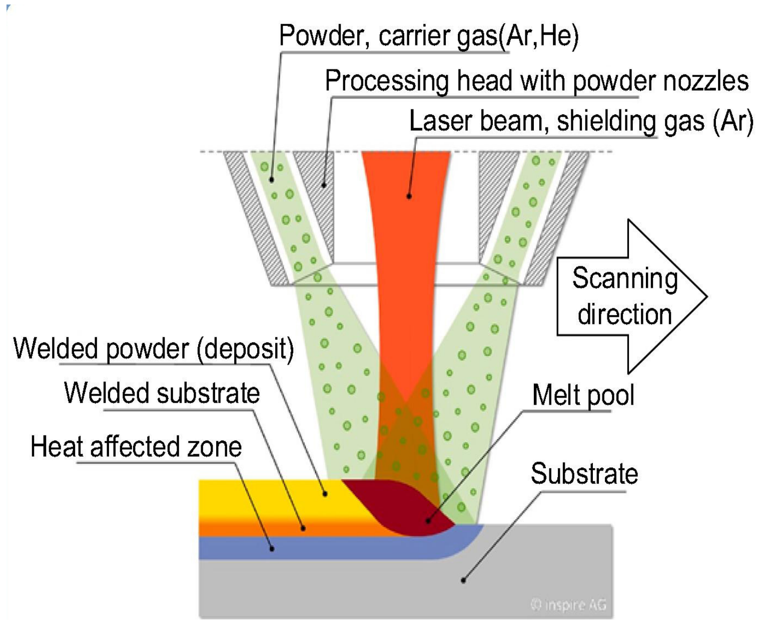


Figure 4 - Overview powder cladding [3]

The type of coatings van Halteren makes

List of used coatings VHT ordered from least to most protection against corrosion [6]:

- Carbon steel + Hard chrome (rarely)
- Enduroq 1
- Carbon steel + Nickel/Hard Chrome
- Stainless steel + Hard Chrome
- Enduroq 2000
- Enduroq 2200
- Enduroq 3

*Only Enduroq is made at van Halteren

Hard Chrome

Hard chrome is very suitable as a tribological surface for cylinder rods, but the corrosion resistance is limited. This is usually applied to stainless steel. It is a cheap coating, hence its popularity. The significant downsides are the health risks during application (Chrome-6) and the resulting ban on using this coating in the European Union. This is why this coating will no longer be applied, and alternatives like Enduroq 1 were developed, which was created to have the same corrosion resistance and costs as Hard Chrome.

The process of powder injection cladding

There are multiple ways of laser cladding, including cladding by wire feeding, pre-placed powder, and powder injection [1]. At van Halteren, the machine uses the latter. Powder injection cladding machines work by injecting the powder using a carrier gas. This stream of gas with powder particles will hit the substrate at an angle. The substrate is locally melted by a high-power laser beam, and the metal powder hitting the melt pool will melt by the heat of the metal in combination with the laser beam. Metal that has not hit the melt pool will either be lost or adhere to hot metal, increasing the surface roughness. The bead, which is spiralised around the rod with an overlap, is a crucial part of the process. This overlap is necessary to limit the surface roughness and to create a more even layer [1]. The overlap also plays a significant role in influencing the hardness [4] of the deposited layer. To achieve a hardness that compares to the source materials' hardness, overlaps of <70% are used [4]. However, this also depends on the size and shape of the nozzle and the melt pool. When the coating is laid down, the thickness of the coatings at van Halteren typically are:

Enduroq 3 – 1.35mm (+0.1 / -0.05mm)
Enduroq 1 – 1.00mm (+0.1 / -0.05mm)

VHT uses the Enduroq brand name for its range of coatings. Different powder compositions are used for the Enduroq 1 and Enduroq 3 coatings (see page 17). Both consist of other chemistries that have their own advantages and costs. Root causes for faults were hard to find in the literature, what appeared to be quite normal in the laser cladding industry. "As per review, identifying the causes defects and problems in laser cladding and suggesting their remedies are rarely found to be presented in the open literature" [5]. So, when research is done on what makes a good process and what needs monitoring, experience from VHT and the literature will need to be combined to develop a good solution. Tests are also beneficial and are done regularly with VHT's cladding setup.

Process parameters

Multiple parameters influence the process; some are constant for the machine that is used, and some can be varied by the process engineer in the WPS' or by the operator, if adjustments are needed. Below, a diagram can be found. This diagram is a visual representation of the most important process parameters, grouped by their category [1], [3], [4], [7].

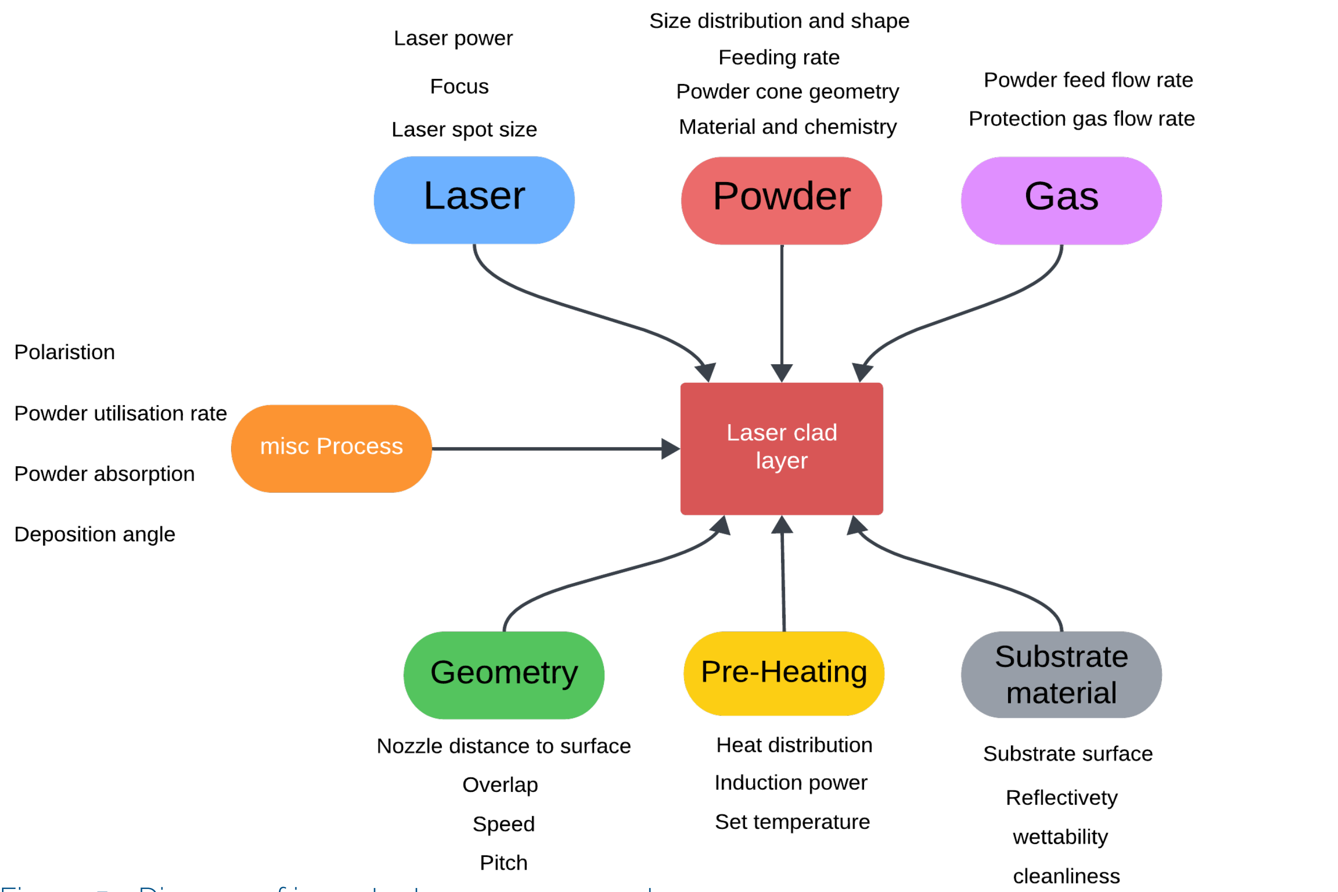


Figure 5 - Diagram of important process parameters

Properties of cladding layer [8]

Geometrical Properties:	Dilution, Clad Dimensions, Roughness
Mechanical Properties:	Hardness, Wear Resistance, Frictional Resistance, Residual Stress, Fracture Toughness, Young's Modulus
Thermal Properties:	Heat Resistance, Thermal Expansion
Metallurgical Properties:	Bonding Ability, Cohesion, Micro-structure, Grain Size, Homogeneity, Dispersion, Corrosion Resistance
Qualitative Properties:	Porosity, Cracking
Post Processing Ability	

All these parameters and more have their own influences on the laser cladding process. The process engineer should know all important parameters the process has to deal with. The operator, however, should know enough to produce and create the specified coating. How much knowledge is needed depends on the machine and the amount of automatization of the process. An important note is that parameters do no relate linearly to each other, which means that e.g. a doubling in laser powder does not mean that one can double the powder feed onto the process. In the following sections, the parameters are promptly explained, and normal ranges are given. Also some clues to how the parameters influence eachother are given.

Another thing to note is that most research is done on small cladding systems with much less power and smaller dimensions. It is hard to extrapolate this research to a machine with 5 to 10 times the laser power and a 3 mm spot diameter to a 19x6.7 mm spot. However, of course, the fundamentals of LC are the same.

About the most important parameters

Laser power

The laser power dictates the amount of energy put into the process. The laser that is used at VHT is the LDF 20000-100 from Laserline. It is a 20 kW laser with a wavelength of 900 to 1080 nm. The range of power used in the process generally is around 12 to 15 KW. With a nozzle spot of 19x6.7 (127.3 mm2), this is around 94 to 118 W/mm2; this is a normal range for laser cladding[8]. A too-high power may cause evaporation, and a too-low power may cause holes and porosity. This beams energy should be distributed uniformly, this is something the EMAqS and Xiris cameras can help with monitoring. The laser is a continuously generated beam, so it is not pulsed or mixed. Pulsed and mixed beams have effects on the micro-structure, internal stresses, and Marangoni flows. The wavelength has a significant role in absorption; the current setup cannot be changed, but shorter wavelengths do create better energy absorption.

Laser spot size

Shape and size of the laser's spot at the substrate's position. To place a bead that is as wide as possible, the spot in the LC machine at VHT is shaped rectangularly and has a size of 19 x 6.7 mm. This is a constant value with the type of lens and focus (distance nozzle to substrate) that is presently used at VHT. The laser power will, therefore, be focussed on the 19 x 6.7 mm square on the rod. The rectangular form is helpful for increased productivity and important in the overlapping and pitch settings.

Powder

The powder used for the cladding is one of the most critical aspects of the process, which is why it is essential to understand how differences in powder can influence the process. However, a downside of this being an influential parameter is the amount of control over the powder quality, as an external company produces it. This lack of control makes it essential to check and monitor the quality of the powder received. This is why every batch is looked at with a microscope to count the slag particles. Also, the powder is taken through a sieve. Enduroq 1 and 3 are the coatings applied the most at VHT. The powders used for those two coatings are a "stainless steel-based" powder and a "cobalt-based superalloy". These are described below.

The material of which the powder is made is one of the main factors influencing the corrosion resistance of the coating. This material can be altered to reach the specified resistance to corrosion that is needed for the application of the rod. The powder can be produced in multiple ways, from its base material to gas-atomized and water-atomized, resulting in different particle shapes and sizes. Atomizing with gas cools the molten metal droplets slower than other methods, giving the particles more time to form a rounder shape under the influence of their own surface tension. This rounder shape makes it easier to feed through the hopper and nozzle and prevents the components from wearing out too fast. A visual view of the two options is given in Figure 6.

Size and shape

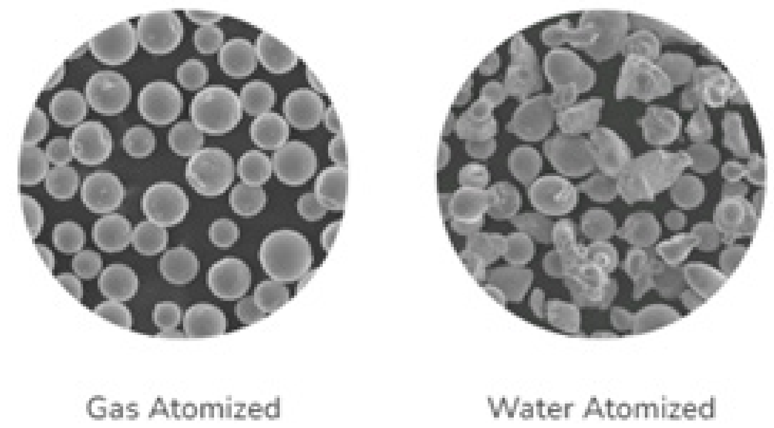


Figure 6 - Dura Metal's explanation of different powder production [9]

The following powders are used for the different coatings VHT makes [9]

Enduroq 1 — Stainless steel-based powder

This stainless steel powder is cheaper than the cobalt-based powder but has the same corrosion resistance as hard chrome-based coatings. It is also wear-resistant enough to be used on the cylinder surface.

Enduroq 3 — Cobalt-based superalloy

Powder particle size: -125 +53 μm (+10%)
This alloy will practically not rust in any normal situation and, because of this, will be almost maintenance-free. However, it is the more expensive powder because of the cobalt and because the process is harder to do at VHT.

When the laser is turned on, the distribution of the powder leaving the nozzle changes. The laser interacts with the powder flow [3], which can change the focus and size of the powder beam. The same applies to the carrier gas flow; adjusting this flow and by this, the speed will deform the powder geometry.

Powder Quality

Different manufacturing procedures and even changes in some manual operations during production can have a big influence on the quality of the powders. Slag is an important factor in this process; VHT found that some manufacturers had different production steps that resulted in an order of magnitude higher particle counts of slag. In production, the metal gets heated and mixed in an oven; this process can be done under a vacuum, an inert gas or air. When this is done under air and later poured into the crucible and gas atomizing setup, there is the possibility of slag ending up in the crucible. This could be an operator tilting the smelting furnace overly far and pouring in the floating slag. This is important because this will increase the particle count of slag (see Figure 7). This increase is significant because of the material properties and the light absorbance of these particles. They will absorb more laser light, and this extra slag will float on the surface of the melt pool, absorbing more light locally and creating hot spots in the melt pool (Figure 8 (a). This has been seen happening at VHT. Apart from the hot spots, the slag will also end up in the coating. When honing the rods, these clumps that do not have a great bonding can come loose and create pits on the surface of the rods. This can be seen in Figure 8 (b), resulting from a lower-quality powder. This amount of slag could vary in each batch; this is why manufacturers that produce under vacuum/inert gas are now preferred.

Powder feeding rate

The powder feed rate is measured in grams per minute, and the range used at the VHT LC machine is something in the order of 80 to 235 g/min. When the latter is used, this results in 14.1 kg of powder per hour. Since 1kg of powder costs up to 100 Euro's, this will result in €1410 of powder per hour. This is one of the reasons laser cladding can be an expensive method.

The powder feeding rate, together with the speed and laser spot size, will determine the thickness of the deposited layer. The more metal that is fed through the nozzle at the same speeds, the higher the molten metal will build up. The slower the nozzle moves over the rod with the same powder flow, the more material will build up, increasing the layer thickness. The absorbance of the laser hitting the powder before hitting the melt pool will decrease the energy hitting the melt pool and keep it from excessive melting or dilution [1]. This is called the "shadow effect" and is explained at page 22.

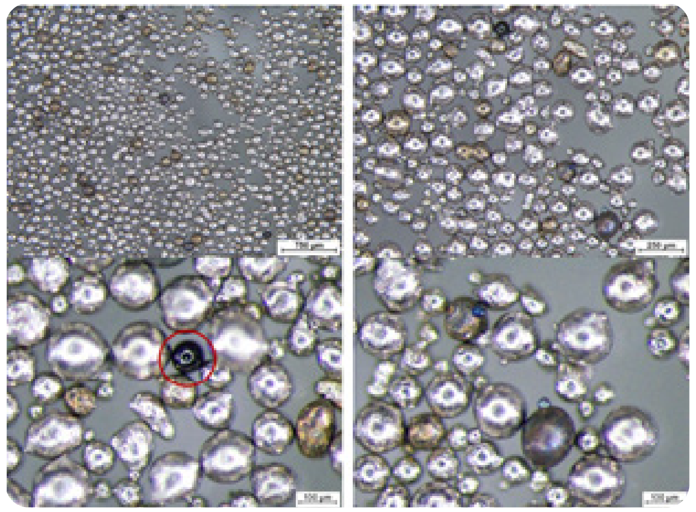


Figure 7 - Slag in powder

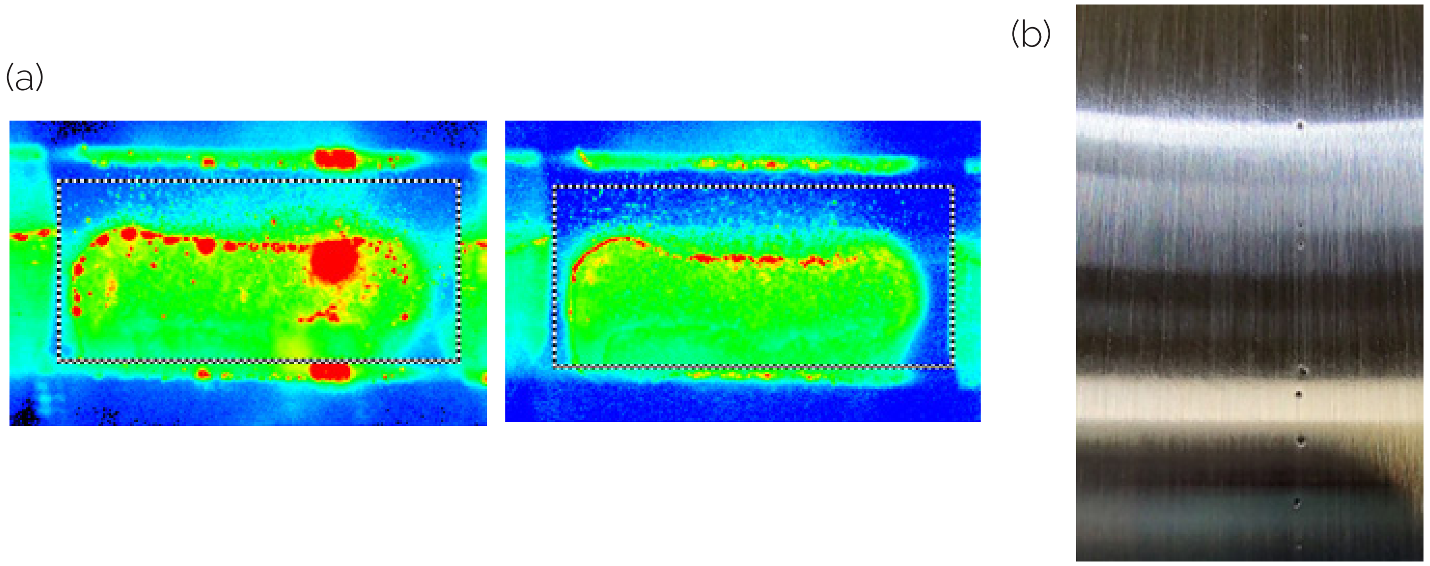


Figure 8 - EMAqS view of weld pool with hot spots (a) and an acceptable pool without (b), picture b shows slag particles coming loose after honing.

Powder cone geometry

The powder cone geometry is defined as the size and shape the powder jet takes on after leaving the nozzle. This shape, place, and size are essential because they determine the powder's interaction with the laser and the place on the substrate where the powder will end up. The density of the powder at different places tells something about the distribution of the added material. In the nozzle configuration at VHT, the powder leaves the nozzle from two different-sized slits that are placed perpendicular to the direction of movement (Figure 9b). The laser is located in the middle of these slits and is focused just above the substrate so that the beam will be slightly wider at the level of the substrate. This is needed to get the correct laser spot size. At some places, the powder will hit the beam before the substrate and melt. This melted powder can then end up in the melt pool, but it can also end up as molten spatters at the sides of the melt pool. The powder focus position can shift in comparison to the laser; at VHT, this is done by a micrometre and in the new laser head from Laserline, it can be done by turning a screw. After discussion with laserline some ease-of-use improvements were suggested to make sure there is a scale around the screw that displays the offset. A new coaxial camera that looks through the nozzle will check the correct position. If the powder focus is set off-centre, powder efficiency can be controlled. If this offset is increased, there will be fewer interactions between the laser and the powder cone, so powder with more slag particles in it can now be used for cladding without too much interaction with the laser. The size of the melt pool increases when laser power is increased; in one case, this reduced the slag inclusions because the melt pool widened and better covered the spatters from the previous path [10]. At VHT, the overlap is almost 50%, so spatters are always covered and melted again by the next pass.

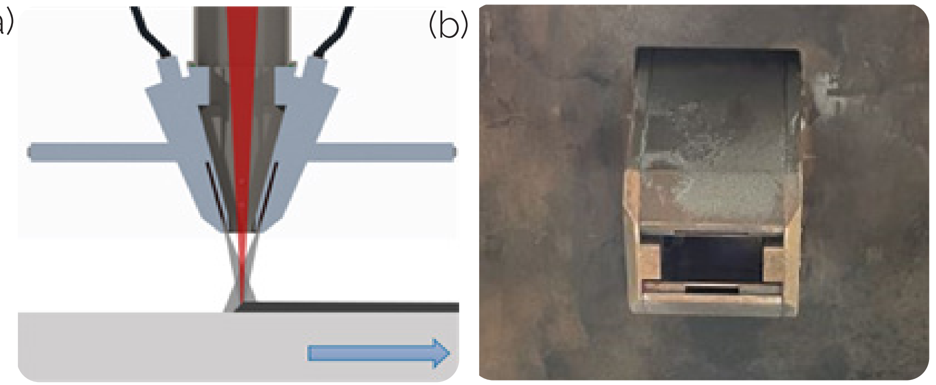


Figure 9 - Nozzle at VHT and the slits in the nozzle (VHT 2024)

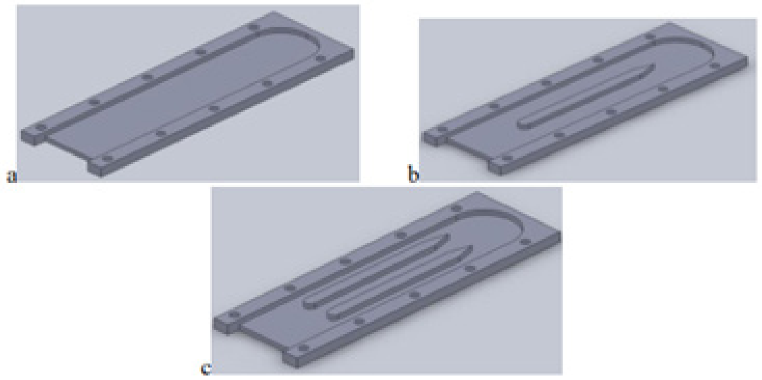


Figure 10 - Powder slits and possible inside geometry, changing powder flows. [11]

Nozzle-to-surface distance

The distance between the nozzle and the substrate is called the working distance, and at VHT, this distance for the LC machine is 33 mm. This distance is crucial because it should match the focus of both the powder cone geometry and the laser focus. They should, at this value for the nozzle to surface length, both be focussed on the substrate, creating the spot size specified (19 x 6.7 mm).

The rod that is spanned and turning may sway a bit because of the way it is bending under its own load, or the centre in which the rod is spanned could be out from the true axis of the rod. This can be measured with the line scanner; the deflection may not be more than 1.5 mm, so a maximum sway of 3 mm is allowed. The LineScanner measures this sway, which is monitored during production.

Cladding speed

The cladding speed is defined as the nozzle's speed relative to the rod's surface, which is, in this case, rotating. In the LC machine, multiple axes move simultaneously to form the spiralised bead around the rod. The nozzle's path relative to the rod can be characterised with a speed. A typical range for this is 1000 to 1500 mm/min for the equipment at VHT. This speed is created by rotating the rod and moving the nozzle along the axis of the rod. In this way, the nozzle only travels along one axis, and the rod only turns to create the spiralised path. To create the desired cladding speed, the speed in the x-direction and the rotational speed have to be calculated for the given diameter and for the needed pitch. This pitch will create a degree of overlap. The machine itself does this calculation.

Overlap

The bead created will always have a varying thickness over its width. In Figure 11 and 12 the typical shape can be seen. The varying thickness means that the edges of the bead will be less thick than the middle part. The deposited material has to overlap to get an even layer thick enough at every position to hone the rod to a flat surface. At VHT, this overlap is 3 to 3.5 mm. The resulting unhoned surface still has grooves when overlap is used, but they are shallow enough to disappear during honing. "A larger overlapping gap between the two successive tracks may result in porosity and holes respectively in a coating" [8].
At VHT, the overlap is rather large, so there is almost no gap. However, pitting is occasionally found in the final product even with this overlapping area. The exact cause is still unknown, which is why more data and better monitoring are preferred. In Figure 11 an overlapping bead can be found.

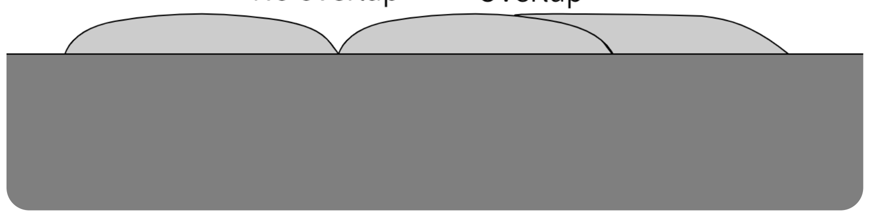


Figure 11 - Overlap between two clad passes

Pre-heating by induction

Some materials require pre-heating to maintain the maximum hardness in the HAZ. However, pre-heating can cause certain secondary effects, such as increased HAZ depth and increased weld pool size/temperature. Pre-heating is done by positioning a big coil over the substrate and inducing significant currents. This current heats the substrate and a value in the WPS (see page 29) specifies the temperature at which the substrate must be heated to comply with the recipe. This temperature ranges from room temperature up to 400˚C. Energy loss of the weld pool occurs mainly by conduction and less by convection or radiation [12]. Pre-heating will lower temperature gradients from the weld pool to the bulk material, as shown in Figure 12. It will also increase the powder catchment efficiency as the welt pool size is increased [12]
Quick cooling times can result in a more brittle area susceptible to cracks. This is because the grain size locally will be bigger when the grains have a longer time to grow before they are completely frozen. Induction heating increases the heat-affected zone (HAZ) in depth and width (Figure 13), which can lead to increased dilution. It's crucial to balance the laser and induction energy to maintain control. Dilution of the coating with the bulk material is not preferred due to increasing iron content and difference in corrosion resistance of the two materials.

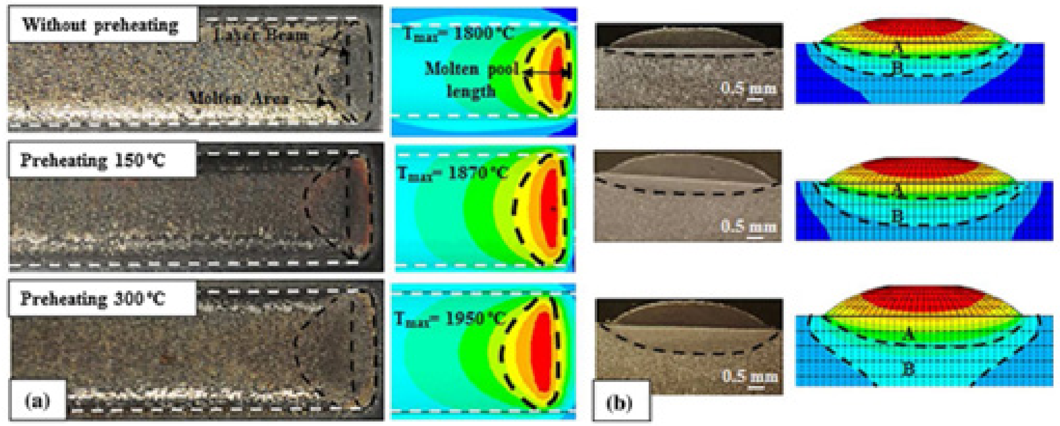


Figure 12 - Simulated and tested influence pre-heating [13]

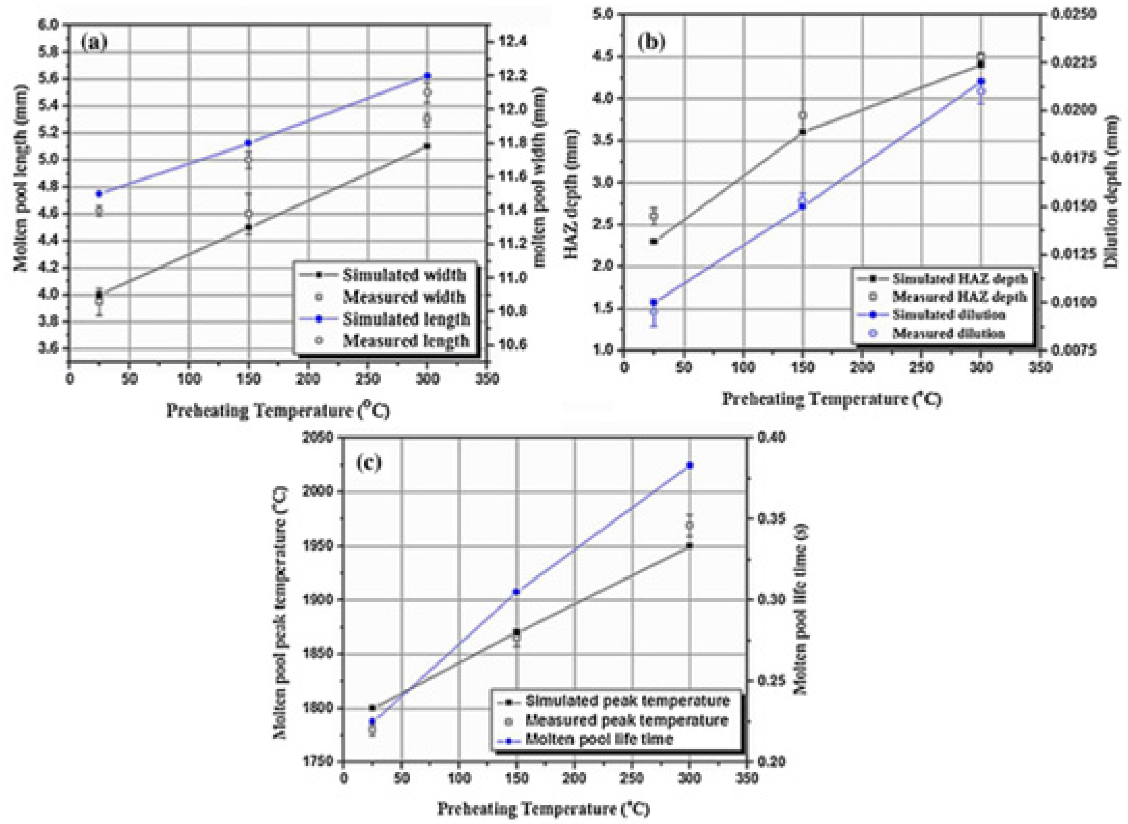


Figure 13 - Positive relations pre-heating on molten pool length (a), HAZ- depth (b) and peak temp (c). [13]

Flow rate carrier gas

The powder is supplied to the weld pool by the use of tubes; to move this powder through the tubes, gas is used. This gas flow can be adjusted to change the speed of the powder and the powder cone geometry. This flow proved to be of large influence on the clad during testing with a new nozzle.

Flow rate shielding gas

Hot metal will oxidise quickly, to stop this from happening in the substrate and coating layer inert gas is supplied that displaces the oxygen and so oxidation will be stopped.

Weld pool temperature distribution

The temperature depends on the exact setting but usually fluctuates between 1500 and 1900 ˚C. It is essential that the temperature of this weld pool is uniform and not too hot or cold. If it is too cold, the coating will not fuse with the substrate, and if it is too hot, the substrate will melt too much, dilution will occur, and the bead track geometry will change.

Shadow effect

If the laser beam reaches the substrate without obstructions, it will transfer most of its energy to the substrate minus the reflected and radiated heat. The problem is that powder is involved; some parts of the laser beam will come into contact with powder particles. These particles will absorb the light, scatter and deflect some of this light. The scattered light that does not hit other particles will not reach the melt pool and transfer its energy. The particles heated by the laser will hit the melt pool, so this energy is not lost. The amount of light that is absorbed by the particles before hitting the melt pool was measured to be a value of 5 to 24% of the total power [14]. Other research states that it can even be more than 50% of the laser's optical energy [15]. This can change the energy delivery to the melt pool by quite a bit. This decrease in energy can result in a colder melt pool or no melt pool forms at all. Also, when the particles get heated in the gas stream, they can vaporize, melt and become a radiant gas ball [16]. A too-high-density powder stream in the path of the laser will decrease catchment efficiency and increase the laser attenuation [15]. This is another reason that makes the powder cone geometry an essential factor to monitor (see page 34).

Material properties

Table 1 below lists many material properties that could be important during cladding and in the resulting layer. The list is split into two different categories: the substrate and the powder properties. The property type is split into physical properties, chemical properties, thermal properties and mechanical properties.

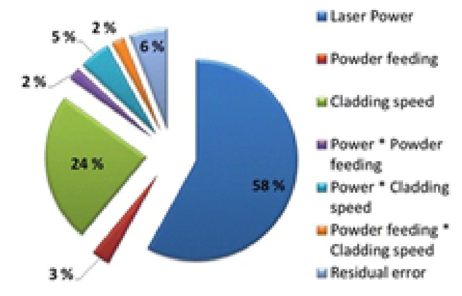
Property Category	Substrate Material Properties	Coating Materials (Powder) Properties
Physical Properties	Reflectivity, Roughness, Wetting Property, Viscosity at Molten State, Physical Properties of Work Material (Effect on the Process)	Particle Size, Shape, Wetting Property, Melting, Mixing of Coating Materials Effect on Coating Properties
Chemical Properties	Reactivity, Chemical Reactivity of Metal (Increases when Melted), Proper Shielding Essential to Avoid Unwanted Phase Formation	Chemical Affinity, Highly Reactive SHS Reactions Between Coating Compounds, May Cause Powder Flying Off from Irradiated Zone
Thermal Properties	Conductivity, Heat Capacity, Melting Point Temperature, Thermal Expansion Coefficient, Compatibility of Thermal Properties of Substrate and Coating, Importance for Coating Sustainability at Various Temperatures, Temperature Rise, Evaporation of Material, Conduction Loss, depending upon Material Thermal Properties of Work Material	Conductivity, Heat Capacity, Melting Point, Thermal Expansion Coefficient are important for Coating Sustainability and Performance in Thermal Loading Conditions
Mechanical Properties	Strength, Modulus of Elasticity, Sustainability of the Coating in Mechanical Loading Conditions, Initial Temperature and Heat Evacuation Conditions, Pre-heated Substrate May Provide Compressive Stress in the Coating, May Reduce Cracking	Hardness, Strength, Modulus of Elasticity, Effects on Sustainability in Mechanical Loading Conditions, Frictional and Wear Performance of the Coatings

Table 1 - Substrates and coating properties [8]

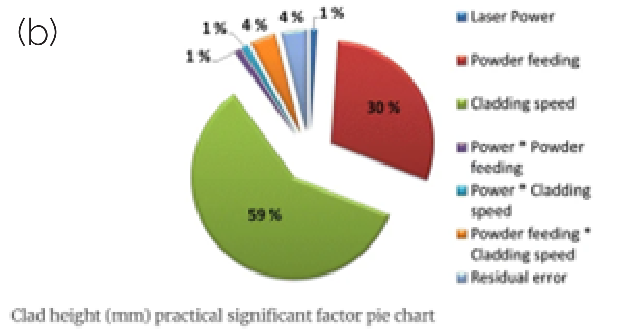
Parameter dependencies

All process parameters involved have complex interactions with each other. Some parameters are measurable, and some cannot be measured live during the cladding process itself. Knowing how parameters influence each other helps to keep the process in check. In Figure 14, two dimensions and one angle are given with a pie chart that shows the most influential parameters.

(a)



(b)



(c)

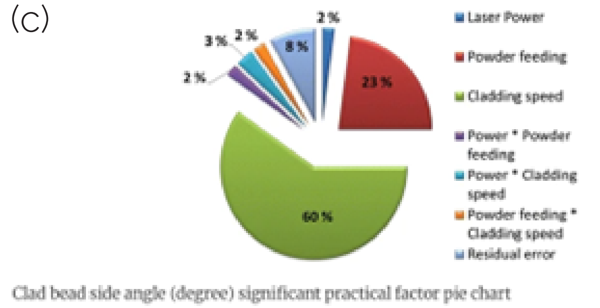


Figure 14 - Pie-charts of parameters and their influence, Clad width (a), Clad height (b) and Side angle (c) [17]

In Figure 14, the cladding speed is the most influential parameter. It is a fixed variable that should be controlled accurately by the motors rotating the rod and moving the x-axis. As the resulting speed is constant, it seems insignificant to monitor. However, at VHT, no sensors or outputs show the exact speed over time. During the data collection phase of this thesis, questions arose about the possibility of extracting this data from the machine. It is an essential parameter for getting good, consistent results, as can be derived from Figure 14. Having sensor data on the exact rotational speed can exclude that parameter if problems during production are found. During monitoring, it can be helpful to look for changes in this speed, as this can create area's that have different properties. The first three charts from Figure 14 give information on the clad geometry and its dependence, excluding cladding speed. Powder feeding is most influential on the clad height. For the width, laser powder is an important variable. Lastly, the powder feeding rate and 'power*speed' are most influential for the clad's side angle with the substrate. With 'power*speed' is meant that one of the factors strongly influences how the other factor affects the outcome. This is logical in the case of power and speed as together they dictate the Linear energy input (J/mm). [17] These findings make the clad height a good indicator of problems with the powder feed. An accurate live measurement of the clad height is preferred. At VHT, a new camera is installed that can give the clad width as an output. So, according to Figure 14, it should be able to notice if there are changes in laser power and cladding speed if the clad width is known. The shadow effect and the distance to the substrate do influence the temperature, so this variation should be seen in this clad width measurement. The powder feeding rate is the most crucial parameter; however, how this stream of powder is delivered is essential; this should be as uniform as possible. The HAZ depth and its micro-hardness are also essential variables. Since these are not measurable during the process, it would be helpful to know what influences them.

(a) (b)

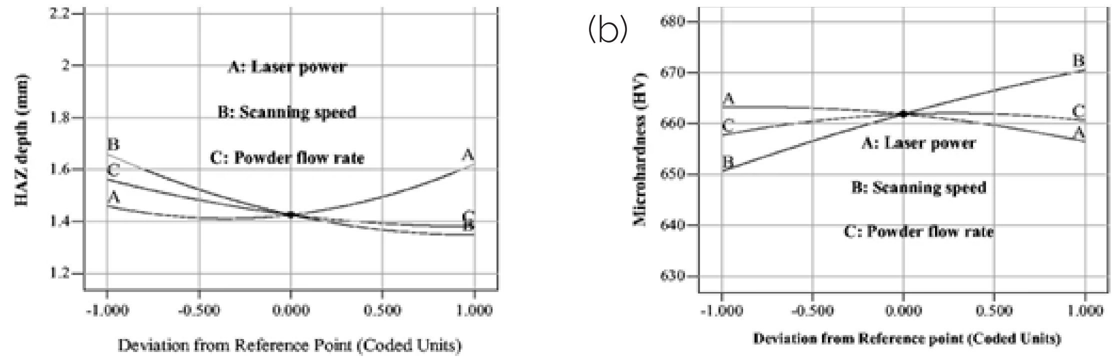


Figure 15 - HAZ depth (a) and Micro-hardness (b) dependency [18]

The graphs in Figure 15 show what changing the parameter (A, B, or C) does to the resulting micro-hardness and HAZ. An increase in laser power increases the HAZ depth, while an increase in scanning speed and powder flow decreases the depth. This makes sense because more power is more heat, and so more volume gets heated. Increased speed will give each area less time to heat, and an increased powder feed will increase the mass that needs to be heated. An increase in scanning speed will increase the micro-hardness, an increase in powder flow will not be as significant, and an increase in power will reduce the micro-hardness [18]. These results also make sense because the increase in power will mean a lower cooling rate and, therefore, lower hardness. The increase in speed causes an increase in cooling rates, so the resulting hardness will be higher. As discussed, pre-heating increases HAZ size and decreases the HAZ hardness. However, increasing the power and pre-heating temperature also has a downside, as the dilution between the substrate and the coating increases. Dilution is not directly measurable but can be derived/estimated from pre-heat temperature, melt pool size, and temperatures. In [19], a computational model was used to predict the dilution rate from those parameters, and they found that there is a relation between them; however, the most significant influence was the melt pool width. "Dilution depends on laser power and powder feed rate, as well as material-dependent factors such as melting point and specific heat capacity. Dilution is minimised when laser power is minimised, and powder feed rate is maximised." [20].

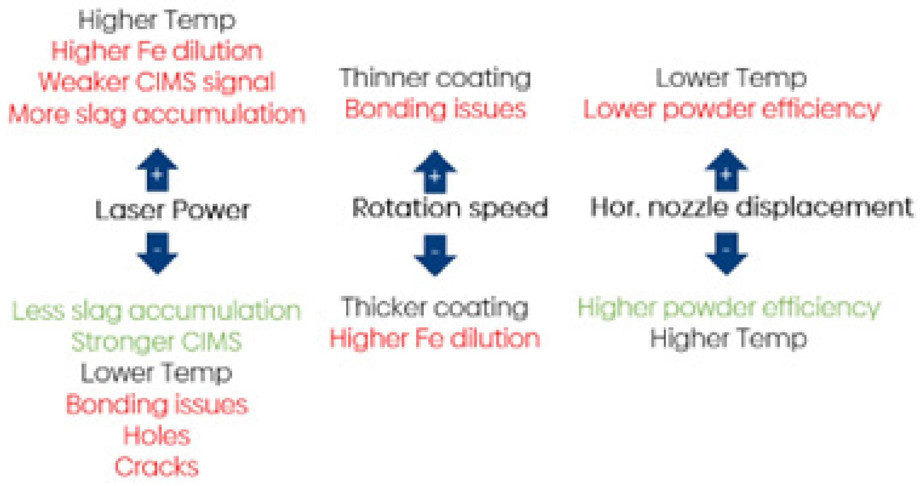


Figure 16 - Considerations in changing parameters (VHT powerpoint)

Figure 16 displays the considerations at VHT for optimising specific parameters. Added here is the CIMS signal, which is a specific groove in the rod that needs to keep its shape during cladding. Increasing the temperature by increasing the power or slowing down speeds can increase the melting of this groove. If this groove gets too deformed, a sensor can no longer measure the position of the cylinder. This makes balancing the power to get the proper hardness even more delicate. A recent event of a thin-walled rod that got overheated and started to bend under its weight also shows that adding more heat has to be done carefully. Supplying too little power creates bonding issues, holes, and cracks.

Process parameter optimisation

Numerous effective methods exist to optimise the discussed parameters. For instance, the Taguchi Method is a powerful tool for swiftly optimising multiple parameters. Additionally, neural networks have demonstrated their potential in optimising the dilution rate in laser cladding, using the laser power, powder feeding rate, and scanning speed as input parameters [21], [7]. These methods offer efficient solutions for complex optimisation tasks. Optimisation of input parameters is not the scope of this thesis, but it is the job of the process engineer. Hence, the dashboard and data collection setup must give the correct feedback for parameter optimisation.

Laser cladding on a cylinder

To deal with 'back reflections' into the nozzle, horizontal and vertical offsets are introduced [22]. The nozzle's height and offset from the centre of the rod are set according to calculated offsets that depend on the rod diameter and the layer thickness. In general, the thicker the layer, the smaller the offsets, and the larger the diameter, the larger the offsets. A larger diameter means that more offset is needed before the surface of the substrate has enough of an angle relative to the nozzle so the reflection of the laser beam will not reflect back into the optics. However, the offsets given here are only advice. In practice, the machine calculates these offsets from the input diameter and layer thickness. The diameter is critical because this metric is used for the rotational speed and the position of the nozzle without the offsets applied. The layer thickness setting in the VHT machine does not change anything in the process apart from the offsets (powder flow and scanning speeds are separate settings); this value, therefore, is used to tweak the position of the nozzle if the clad is not optimal. Increasing offsets causes the powder efficiency to drop because of the angle of the substrate. If the same powder flow and scanning speed are used, this decrease in power efficiency will reduce the layer thickness. Therefore, when analysing the parameters of a cladding layer, it will be essential to keep track of the offsets used and whether the actual layer thickness is used for the calculation or another value is used to decrease back reflection, which may be needed in certain situations.

Given variables:
rd = rod-diameter
lt = cladding layer thickness

Variables that are calculated:
oh = horizontal offset
ov = vertical offset

offset horizontal [oh]:

$$oh = (-0{,}0721 * lt + 0{,}1945) * rd$$

offset vertical [ov]:

$$ov = \frac{rd}{2} - \sqrt{\left(\frac{rd}{2}\right)^2 - oh^2}$$

Figure 17 - Theoretical formula's Fraunhofer [22]

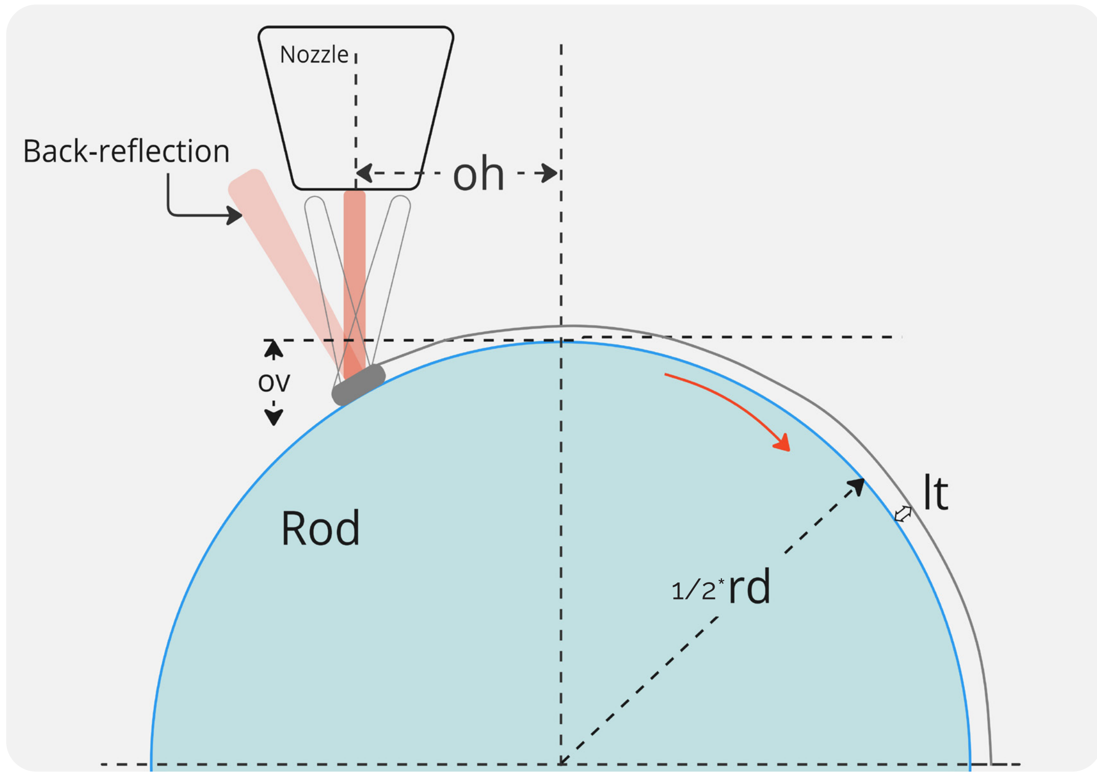


Figure 18 - Laser cladding on a rod, including the offsets

High-capacity and high-speed laser cladding (HSLC)

When the cladding machine at VH was bought, the choice fell on a high-capacity laser cladding system (HCLC). This system had a high-powered laser, 20 kW, and a big rectangular nozzle. This made it possible to clad with powder flows of 235 g/min with ease. The other option, developed by Fraunhofer ILT, was Extreme High Speed Laser Application (EHLA). Outside of Germany called High Speed Laser Cladding (HSLC) [23]. In HSLC, a less powerful laser is used, but the powder focuses inside the laser beam, heating and melting the powder before it hits the shallow melt pool. In this way, less heat is input into the substrate. The advantage of this is that way less dilution can occur. This makes it possible to make thinner coatings of 20-300 µm that have the correct coating properties at the surface without diluting [23]. Because it takes less time to heat only the powder instead of making a melt pool where the powder is melted, this process can be 10-100x faster than traditional cladding. "Moreover, the layers are smoother, with roughness reduced to a tenth of typical values for Laser Material Deposition" [24]. This reduced roughness can make it possible to have thinner layers that require less honing until the layer is smooth and can be polished. Looking at the speed at VHT, which is already high with 1000 to 1500 mm/min, it is nothing with the 300m/min HSLC can achieve [25]. However, the width of the bead that HSLC lays down is much smaller, and when overlap has to be used, the difference in cladded area is much smaller. Around 0.9 m² per hour can be cladded at VHT (1.5m/min, 19mm width, 50% overlap), and HSLC can do 2.0 m² per hour [25]. However, when using HSLC, one may require up to 4 layers to get the 800 µm desired for the layer thickness at VHT as the typical thickness ranges between 200 and 250 µm.

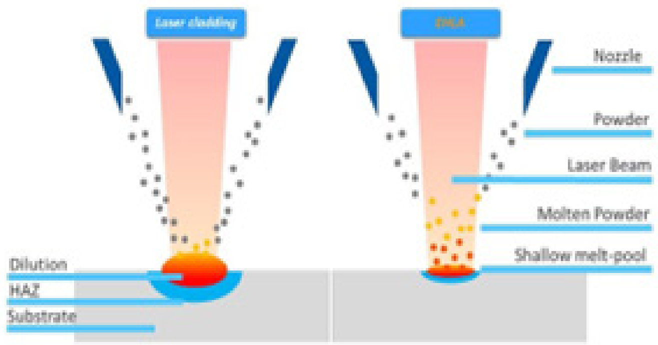


Figure 19 - The difference between HCLC and HSLC

SEM analytics of clad beads

In the search for innovation and cost reduction in the long run, VHT is looking at acquiring a scanning electron microscope. With this microscope, the ability to understand the materials that VHT works with can be better understood without having to send them to a lab. For laser cladding at VHT, this has multiple advantages. From tests, experience, and the recordings of the new camera, it is known that the quality and composition of the cladding powder can vary. This can result in unexpected cracks without any other noticeable difference in the process. This is why the powders are regularly checked under a microscope to see the shape, colour, and size distribution. However, the powder samples and cladding samples sometimes require further analysis. This is when samples are sent to labs for testing. However, this is a costly undertaking. This is why VHT is looking at the possibility of doing these tests in-house. For the powder samples, this means that the shape and composition of individual particles can be studied. The composition is determined with energy-dispersive X-ray spectroscopy (EDS). However, it will also give more insight into the composition and structures in the deposited laser cladding coating. In Figure 20, a cobalt-based laser cladding bead profile can be seen. This was a low-powered clad, and the different grains are given a colour. These colours visually represent the orientations of the grains in the polycrystalline material (Orientation Imaging Microscopy) using a colour key. In this way, the different sections of a clad can be studied like the substrate, coating, HAZ, and the dilution and mixing that occurs. In this way, more insight can be gathered into the effects of the process parameters on the micro-structure of the coating. Having quick access to this kind of information can help tune settings and detect problems.

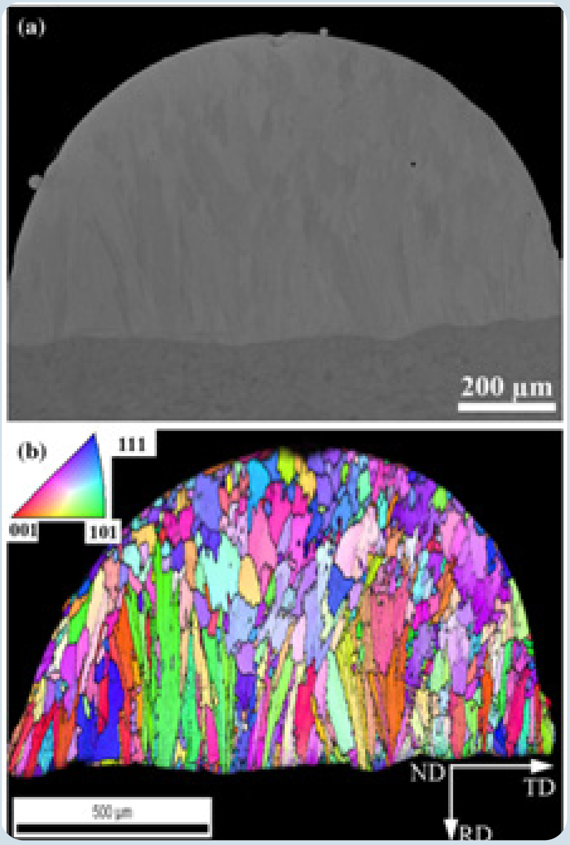


Figure 20 - SEM image (a) and colored SEM image (b) of a cobalt-based clad dissection [65]

Cladding defects and difficulties

Multiple errors can occur during cladding and affect the quality of the coating. These can be machine-specific or process-specific. The fault tree analysis in the appendix contains some conventional faults and errors that happened at VHT. The list below isn't exhaustive but gives some examples of what can go wrong during cladding, multiple of the listed problems did at some time occur at VHT.

Power problems

"Appropriate laser power will reduce cracks, voids, and produce cladding layers of good quality and performance." [3]
Problems concerning the power level and the resulting melt pool temperature are some of the most common problems. It is also something that can be solved relatively simply by increasing or decreasing the power that is used for cladding. However, the power should still stay between the power levels specified in the welding specifications.

Laser power	*too high*	*> crack and deform [3]*
	too low	*> local pill and voiding[3]*

Marangoni flow

Thermo-capillary (Marangoni) flows are the dominating factors in convection mechanisms [8]. The surface tension of the metal will change with the temperature gradient and chemical composition inside the melt pool, surface tension decreases when temperature increases. The thermal expansion of the metal hitting the laser also causes flow and the force of this expansion acts opposite to the laser movement. In conclusion, Marangoni flows cause the mixing of materials and widening of the melt pool [8]. It is also stated that sometimes it causes inhomogeneous mixing of the substrate with the coating [8] This is something that has happened at VHT and will be explained later.

Cracks Holes and porosity [8]

Cracks, holes, and porosity in work-pieces can result from various factors. Grease on the work piece surface, moisture in the shielding gas, and improper power settings increase the likelihood of defects. Using the correct power combination and incorporating ultrasonic vibration may help reduce holes. Overlap inclusions also contribute to these issues.

Cleaning

If the substrate is not clean, this can cause local problems in the layer. For example, grease, dirt and metal chips, can be embedded or heated by the laser and cause defects like gas-inclusions or cracking. This was tested by VHT where the rod was contaminated with grease, cooling liquid, chalk, black marker and other markers. The chalk and black marker caused some problems but the effects weren't as bad as expected with the cooling liquid and grease. However, all the rods entering the cladding machine are cleaned so this shouldn't cause regular issues but there was a case, explained on page 66 where it did cause problems.

Laser cladding at VHT

Apart from literature research about the process, a lot can be learned about VHT's process and working procedures. Also, some practical examples of situations that happened at VHT can give ideas on what data to include in the interfaces. This chapter will discuss this specific laser cladding process and the working procedures at VHT.

Tribology specifications cylinder rods

At VHT the tribology specifications of cylinder rods are an essential part of the design process and why such a specific coating is needed in the first place. The cylinder rod has to slide through the seal in the cylinder. This should create an interface that does not leak and can handle the high pressures that are used in a cylinder. For this to happen without problems, the surface of the rod should have specific properties. When this deviates, the seal can be damaged or start to leak. Furthermore, dirt and other particles can damage the rod. This makes the structure of the running surface, the surface that slides through and interacts with the seal, most important. This would not be possible without a corrosion-resistant layer on the outside of the rod. If this surface starts to erode and rust, it will change the surface properties and damage the seal. Also, the structure of the rod will determine if stick-slip behaviour will occur; this is not preferred as it can damage the rod. The roughness profile is a result of the way VHT hones the rods. The honing stones will pass over the surface in two angles, creating a profile where the grooves intersect each other at that angle. Profiles will be checked with a profilometer to see if the correct pattern has been created. In general, the outside surface should have a tight roundness tolerance, a tight straightness tolerance, low roughness and, of course, high corrosive resistance.

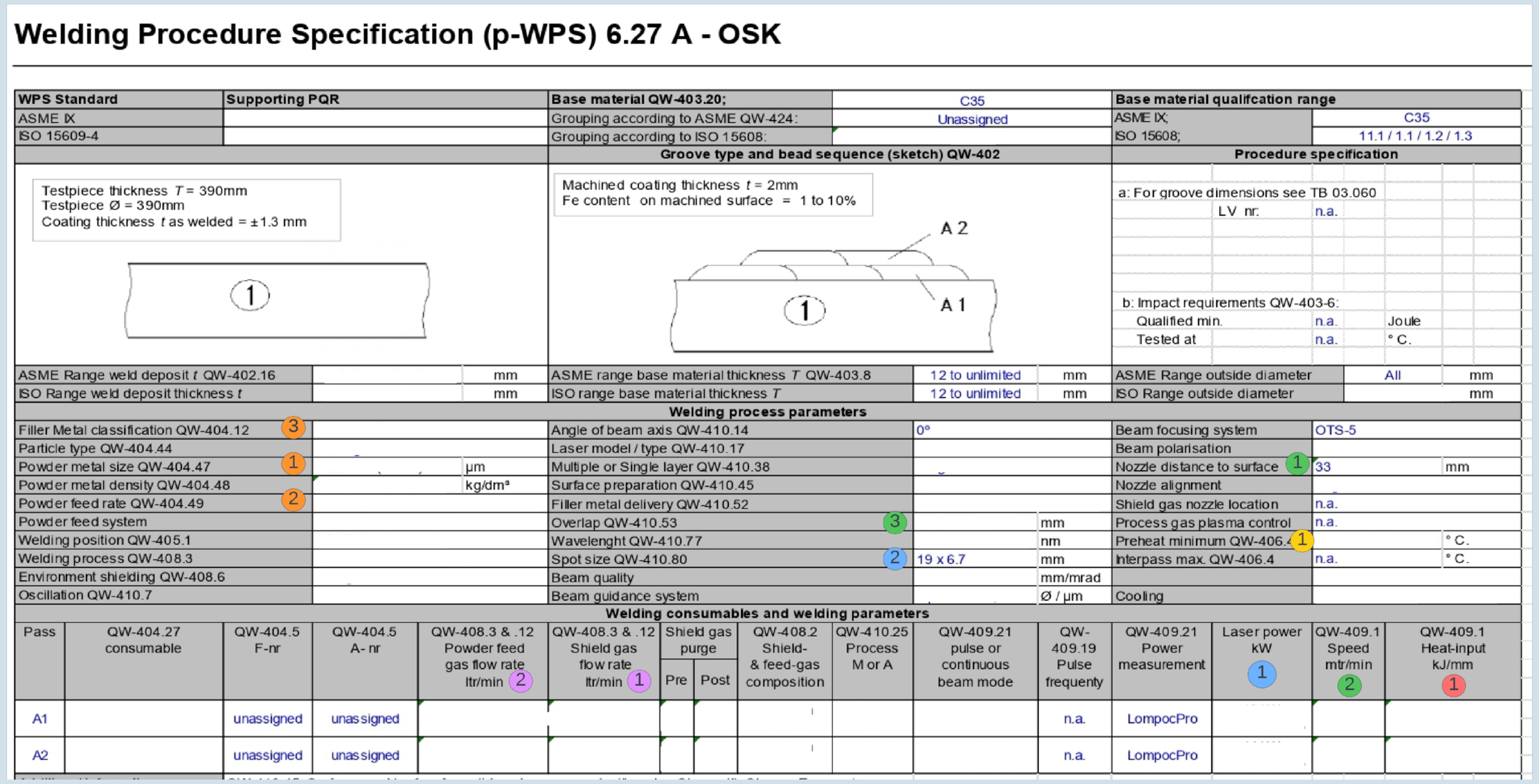
Furthermore, wetting the rod surface with hydraulic fluid is important. This means that the metal surface should be able to be wetted by the hydraulic oil that is used. Special types of oils exist for use with different cylinders and materials. [6]

Welding procedure specification

To create the desired coating, a welding procedure specification (later called WPS) has to be made. This is done by the process engineer and given to the operator to make the coating. This is a form that exactly specifies all the parameters and dimensions of the coating and how it should be applied. An example of this form can be seen in Figure 21. This form includes almost all crucial variables that are important for the process, including those that the operator should input into the systems. Some important parameters are listed in the legend and shown in the WPS. It also includes some standard information about the process that is always the same when the same machine is used for the coating. Things like power measurement and beam guidance systems are inherent to the LC machine at VHT.

- Laser power 1
- Laser spot size 2
- Powder metal size 1
- Powder feeding rate 2
-Powder name 3
- Nozzle distance to substrate 1
- Speed (bead over substrate) 2
- Overlap 3
- Pre heating by induction 1
- Shielding gas flow rate 1
- Powder feed gas flow rate 2

-Heat input
(laser power kJ/min devided by speed mm/min) 1



Welding Procedure Specification (p-WPS) 6.27 A - OSK

WPS Standard	Supporting PQR	Base material QW-403.20;	C35	Base material qualifcation range	
ASME IX		Grouping according to ASME QW-424:	Unassigned	ASME IX;	C35
ISO 15609-4		Grouping according to ISO 15608:		ISO 15608;	11.1 / 1.1 / 1.2 / 1.3

Groove type and bead sequence (sketch) QW-402

Testpiece thickness *T* = 390mm
Testpiece Ø = 390mm
Coating thickness *t* as welded = ±1.3 mm

Machined coating thickness *t* = 2mm
Fe content on machined surface = 1 to 10%

A 2
A 1

Procedure specification

a: For groove dimensions see TB 03.060
LV nr: n.a.

b: Impact requirements QW-403-6:
Qualified min. n.a. Joule
Tested at n.a. ° C.

ASME Range weld deposit *t* QW-402.16		mm	ASME range base material thickness *T* QW-403.8	12 to unlimited	mm	ASME Range outside diameter	All	mm
ISO Range weld deposit thickness *t*		mm	ISO range base material thickness *T*	12 to unlimited	mm	ISO Range outside diameter		mm

Welding process parameters

Filler Metal classification QW-404.12 (3)			Angle of beam axis QW-410.14	0°		Beam focusing system	OTS-5	
Particle type QW-404.44			Laser model / type QW-410.17			Beam polarisation		
Powder metal size QW-404.47 (1)		µm	Multiple or Single layer QW-410.38			Nozzle distance to surface (1)	33	mm
Powder metal density QW-404.48		kg/dm³	Surface preparation QW-410.45			Nozzle alignment		
Powder feed rate QW-404.49 (2)			Filler metal delivery QW-410.52			Shield gas nozzle location	n.a.	
Powder feed system			Overlap QW-410.53 (3)		mm	Process gas plasma control	n.a.	
Welding position QW-405.1			Wavelenght QW-410.77		nm	Preheat minimum QW-406.4 (1)		° C.
Welding process QW-408.3			Spot size QW-410.80 (2)	19 x 6.7	mm	Interpass max. QW-406.4	n.a.	° C.
Environment shielding QW-408.6			Beam quality		mm/mrad			
Oscillation QW-410.7			Beam guidance system		Ø / µm	Cooling		

Welding consumables and welding parameters

Pass	QW-404.27 consumable	QW-404.5 F-nr	QW-404.5 A-nr	QW-408.3 & .12 Powder feed gas flow rate ltr/min (2)	QW-408.3 & .12 Shield gas flow rate ltr/min (1)	Shield gas purge Pre	Shield gas purge Post	QW-408.2 Shield- & feed-gas composition	QW-410.25 Process M or A	QW-409.21 pulse or continuous beam mode	QW-409.19 Pulse frequenty	QW-409.21 Power measurement	Laser power kW (1)	QW-409.1 Speed mtr/min (2)	QW-409.1 Heat-input kJ/mm (1)
A1		unassigned	unassigned								n.a.	LompocPro			
A2		unassigned	unassigned								n.a.	LompocPro			

Figure 21 - Edited WPS Form used at van Halteren, important parameters are numbered to the list of important process parameters

Wear of nozzle

The nozzle focuses the powder onto the substrate, this can cause wear to the nozzle channels. Because of this, the channels of the nozzle will widen. This will result in a distorted powder focus. At VHT, this already resulted in a layer that later caused some problems during the operation of the said cylinder. In this particular case, the problem lay in the worn nozzle combined with the use of an older type of steel. In this case, older cylinder rods were coated with the new Enduroq 3 coating. How the powder flow changed is unclear at VHT, however some basic things are happening. The channel is widened because of wear; now, the same mass flow of shielding gas will create lower gas speeds in the nozzle because of this widening. This lower airspeed widens the stream's powder concentration, leaving the nozzle. Because of this, less powder was focused into the weld pool, and its temperature could increase. This increase in temperature increased a kind of mixing in the process. The older type of steel that this cylinder was made of seemed sensitive to this kind of mixing, and lumps of the substrate material came loose and ended up in the coating layer. So, clumps from the substrate were mixed inhomogeneously with the coating, which has a different effect from dilution.

This problem was solved by replacing the nozzle and changing the one-layer coating process to a two-layer process, which helped limit this dilution. Understanding the condition of the nozzle is a crucial parameter in the process, demanding the attention of the operator, maintenance, and process engineer. This awareness led to the prototype of the laser powder checker, a topic that will be further discussed in the project, as well as Fraunhofer's own scanner, which will also be explored later.

It is crucial for the operator to be able to detect nozzle wear in time, as the speed at which this wear will cause notable effects on the layer is currently unknown. The maintenance people should know when and how to perform the maintenance on this part. The process engineer should know how it influences the process, what the signs are and how to instruct the operators. When the wear can be measured, it can be added to the interface as an indicator.

Standard recipes and materials

There will be an focus on Enduroq 3 settings for the dashboard because this is one of the most used coating. However, the new interface should be able to work with any recipe. So the recipe could become a variable in the new dashboard. Some of these recipes are found in Figure 23.

Recept Nr.	Receptnaam inclusief materiaal & laagdikte	Lassnelheid mm/min	Gram / min	Voor-verw.	Spoed	Te gebruiken op materialen
1	EQ1 S355 / 1,1mm/ 160g	2000	160	Nee	9mm	S355
2	EQ3i S355 / 1,35mm/ 235g	800	235	Nee	16mm	S460/S420/S355
8	EQ3 S355 / 1,35mm/ 235g	950	235	Nee	16mm	S460/S420/S355
9	EQ3 25CrMo4QT / 1,35mm / 235g	950	235	Ja	16mm	25CrMo4QT
10	EQ3 25CrMo4QT / 1,35mm / 235g / D<100mm	950	235	Ja	16mm	25CrMo4QT
14	EQ3 42CrMo4QT / 1,35mm / 235g	950	235	Ja	16mm	42CrMo4QT/25CrMo4QT
26	EQ3i S355 / 1,35mm / 235g / D <100mm	800	235	Nee	16mm	S460/S420/S355
30	EQ3 S355 / 1,35mm / 235g / D <100mm	950	235	Nee	16mm	S460/S420/S355
45	EQ3 C35 / 1,35mm / 235g /OSK WPS-6.20A	950	235	Ja	16mm	C35

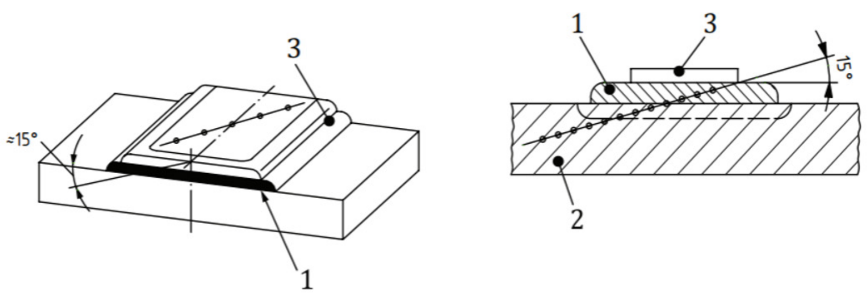
Figure 23 - List of recipe's used at VHT

Ultrasonic vibration-assisted cladding

Ultrasonic vibration-assisted laser cladding is a method that tries to improve mechanical and tribological properties. By using ultrasonic vibration the formation and disintegration of cavitation bubbles are influenced. This particularly has an impact on the micro-hardness and friction wear [27].

CIMS

Knowing how far a cylinder is extended is essential in controlling hydraulic cylinders. One way to do this is with a CIMS sensor and a CIMS profile underneath the cylinder's coating. The sensor can detect this profile and output the cylinder's movement. The profile on CIMS rods have peaks and valleys. The difference between the peaks and the valleys is 0.25 mm, which must be kept intact during cladding. So, this adds a challenge to the process. Furthermore, the varying distance from the nozzle to the uneven substrate can mean different things to the process. The laser spot has a different focus at the peak and bottom, increasing or decreasing the area over which the power is divided. Also, the powderstream focus can change, and so can the beam shadowing effect. Less powder in the laser spot means more light hitting the substrate and the laser has less material to melt, this reinforces each other. These discussed effects are noticeable on the shape of the weld pool during cladding and should be observed.



Key

1 intermediate layer, if necesssary
2 parent metal
3 hardfacing or corrosion resistant overlay

NOTE Distance between the measuring points along the 15° line approximately 1 mm.

Figure 22 - Required hardness traverse testing for overlay ISO 15614-7 [28]

Quality control

After the rod has been coated and honed the quality will be checked. The faults that were discussed in the previous chapter can happen and this will impact the resulting quality of the rod, The checks that van Halteren performs after cladding are the following.

Layer thickness

An ultrasonic device will be placed on the rod that can accurately measure the layer thickness. This thickness range after honing varies around 0,8 mm (800 μm). The resulting thickness is primarily a result of the honing process in combination with the deformation of the rod by the release of stresses after pre-heating. This is why stress-relieved rods are bought at VHT. The line scanner's measured thickness data says something about the thickness and geometry before honing it down, as it should be sufficiently thick to be able to remove enough material.
Requirement: Nom ≥ 600 Min ≥ 400 (μm)

Iron content with XRF meter

An XRF meter uses radiation to see the material's emission after being hit with this radiation. With this data, the XRF meter can output a report of the contents and the quantities of certain elements in the metal. In this case, it is used to measure the Iron content. This value is around 1.5% in Enduroq 3 coatings. It may not exceed 10% and preferably <3%
Requirement: ≤ 10%

Surface roughness test

The roughness of the surface is an important parameter for the functioning of the cylinder. This is measured by a roughness meter and the Ra has certain requirements, the results can depend on the deposited layer and the honing operation that was used.
Requirement: Ra (μm) ≥0,10 - ≤ 0,35

'Salt-towel' test

This is a corrosion test that is done to test the coating. A solution of tap water with sodium chloride (NaCl - kitchen salt) 40 (+/-5) g/l and vinegar is made so the pH of the solution is between 4 and 5. A long fabric towel is then drenched in this solution and wrapped around the cylinder, leaving it for a specified time, usually one day. Afterwards to towel is removed and both the towel and the rod are checked for rust. All the spots found will be noted and inspected. Requirement: Imperfections of >0.2mm that continue until the substrate should be repaired and noted in NCR. Maximum of 3 indications per m² and 1 indication per running meter. After repair, another salt-towel test is done; now, no indications may be found on the rod.

Corrosion tests

New and old coatings are continuously tested in two salt-water chambers, where they are exposed to acidic salted water to check for corrosion. This is done in specific regiments and is used to simulate more extended periods of corrosion.

Visual inspection

The absence of scratches, pits, and cracks is checked and should be repaired if found. The surface should be uniform and smooth.

Liquid dye penetrant test

A purple-colored liquid is applied to the rod, this is left to rest and later a white powder is applied. The places that have pits and cracks will now be visible purple. This makes it possible to detect cracks and pits. The amount of resulting reparations can be taken as a quality measurement.

Hardness testing

Laser cladding products have to adhere to certain standards, one of them being ISO 15614-7. An overview of this standard can be found in Figure 22. This Figure shows the places where the hardness is measured. Furthermore, this standard describes the maximum hardness allowed in the weld/coating. In the section explaining the importance of pre-heating by induction, rapid cooling can increase hardness. So, creating an area with too-high hardness can be a fault in the process. This is measured at VHT by the Vickers hardness test HV5. In the standard, a maximum value of 380 HV is allowed in the Heat-Affected Zone, so the substrate's hardness that has changed because of the heat may not exceed 380 HV. Hardness in the different zones can be estimated from the input parameters [69] and cladding speed is most influential.

04 Monitoring and process control research

When it is clear what a good cladding layer looks like and what the preferred parameters are, it is interesting to see how this can be monitored and controlled. Hence, the process stays within its margins and results in a high-quality layer. This chapter explains how to set control limits and monitor the process.

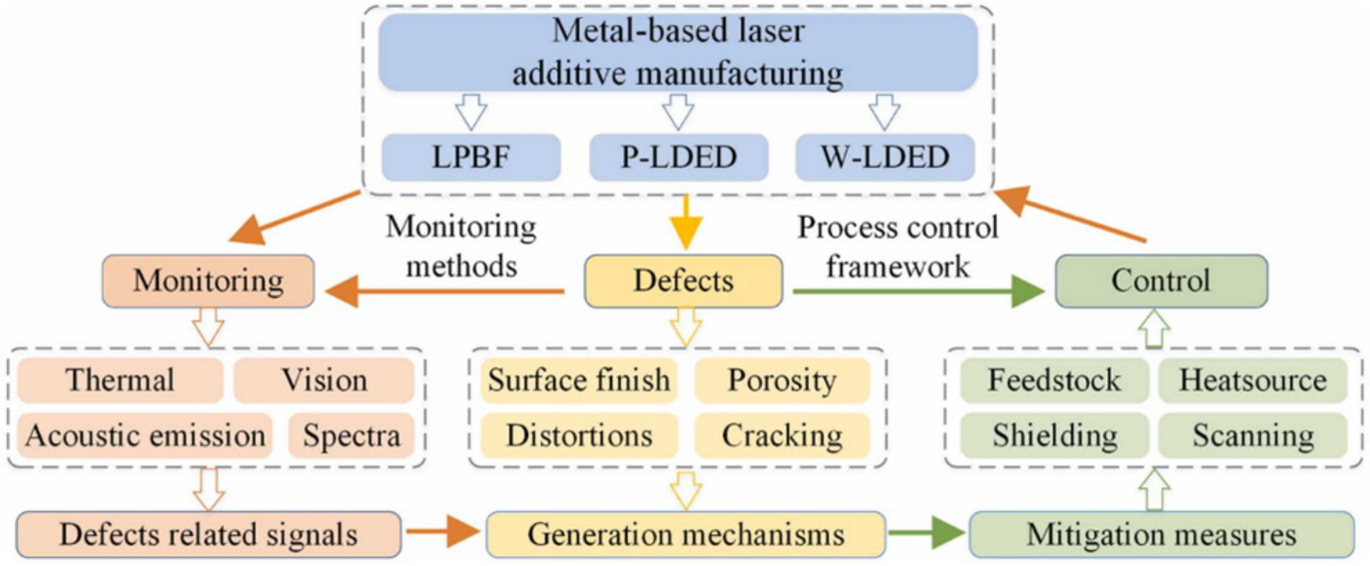


Figure 24 - Monitoring and control diagram [29]

This diagram (Figure 24) shows the monitoring and control process in metal-based laser additive manufacturing (MLAM). It gives a good overview of how quality is monitored using thermal, visual, acoustic, and spectral means. This creates signals about defects that can give input for the generational mechanisms, and mitigation measures can be taken from this. These measures add to the control part of the process that then gets monitored again, completing the circle. This control could be the OP or PE changing process variables, automatic systems controlling a variable, or even ML algorithms controlling the process, as proposed in the paper [29]. However, for each of the control options, monitoring quality and efficiency is essential, as well as the coupling between this and the defects/quality. Clear and usable data, in combination with known generation mechanisms, make it possible for the control parts to be done with more knowledge. However the LC machine is just one piece of the whole process as "Most people think of a process as a machine or task, but it is more complex than that. A process is the entire system of machines, raw materials, people, procedures, environment, and measurements, used to make a product." [70].

Monitoring tools

To keep track of the LC process multiple sensors and tools are used. Some of these sensors have some kind of controlling software coupled to them. Some, like a sensor that senses if a door is closed, only prohibit function if necessary to ensure safety. But others will relay more complex data that is not coupled to any kind of control mechanism. This data is there to inform the OP and PE of the state of the process. This ensures that the operators and process engineers have enough data to make informed decisions on controlling the machine. To find ways to make better use of those sensors the first thing to know is, what is used and what is available. The table below shows the types of sensors used at van Halteren and some additional sensors that could be used.

What?	What is it?	Why?	Used at VHT
Pyrometer	High-temperature laser point sensor which is coupled with the control system of the inductor	Keep track of substrate temperature and adjust power to the measured temp. (Infrared signals for temperature measurements can be influenced by laser power in certain set-ups [26].)	Yes
Line scanner	Distance sensor over a line	Used to estimate the layer thickness and see the weld contour, as well as measuring the rods distance to the arm.	Yes
Coating thickness meter	Measures the layer thickness in comparison to the uncoated piece of the rod	To know the layer thickness more precisely after coating, used for checks	Yes
EMAqS (NIR thermal camera) based on Manta_G-033B	Camera-based temperature measurement can be coupled to a control system, but not used at VHT	Gives the OP and the PE an heat map of the current weld pool, possibility of automatic temperature adjustment	Yes
Cover slide monitoring module	Measures the temperature of laser aperture cover	If the cover slide is damaged or a metal particle or dust is stuck to this lens the laser will heat this glass and so limit power. This glass protects the more expensive lenses of the laser to the violent process underneath	Yes
Powder flow sensor	Measures the flow of powder at the powder hoppers and just before the nozzle	A deviation in powder can result in a bad layer so keeping track of the right g/min is important	Yes, but the function seems limited
Process camera's	To follow the process from the outside of the machine	Operators can see the looks of the bead that has just been laid down and check it for visual defects	Yes
Xiris Infrared camera	A camera similar to EMAqs, will give a high quality image of the heat coming from the weld pool	This can give the operators a better understanding of the state of the process, detect faults and	Installed during project
Xiris visual welding camera	More zoomed view the cladding process	Gives a high definition view of the melt pool.	Installed during project
Closing sensors	Measures if certain doors/ windows are closed	Protects OP from laser light escaping the cabin	Yes
Speed and control sensors	Measures the movement of the different axes and controls the resulting speeds	To make sure all the axes and rotations of the machine are matching the set speeds by the operator.	Yes
Gas flow and pressure sensors	Measures the pressure in the hoppers and the amount of gas flow through the tubes	Correct gas flow is needed for the shielding of the process and the right powder cone shape	Yes

What hardware to add?

Researchers and companies develop multiple sensors and solutions to help with process control and create more insight into the process. What are important sensors and solutions that VHT has or can add to its cladding system?

Powder flow sensor

This sensor has already been installed; however, it can be improved. This sensor gives a percentage or a count value and does not give a calibrated value in grams/min. Also, the sensor is not used to give warnings when the flow drops too much, which can happen if a tube breaks. The tubes delivering the powder can also leak or clog. An interrupted powder flow can cause overheating of the melt pool, and too little material is deposited. This has already happened and can be noticed quicker if the sensor has a warning connected to it and is more precise. In a paper from 2016 [30], an optoelectronic sensor was developed that can accurately and precisely monitor the flow through the tubes. Also, the company that made the particular machine at VHT, Fraunhofer, developed their sensor to do the same. This is called the POWDERscreen and also uses photo sensors to measure the flow [31]. The downside is that it only works up to 20 g/min with four channels, so 80 grams/min total. This is insufficient to measure the 235 grams per minute VHT regularly uses. VHT has four tubes, and a deviation of ±2g/min total is allowed per tube.

COAXjay sensor box

This is a system made by Fraunhofer that uses multiple sensors as inputs and monitors the process. "It detects process fluctuations, contaminated protective glass, powder feed fluctuations, and changes in process temperature" [32]. It records this data and displays it on a user interface. This safeguards the process, protects the technology from overloads, and supports predictive maintenance. It looks like a further developed control system of what is present at VHT.

LineScanner

This sensor has been installed at VHT and measures the profile on the turning rod of the uncladded area as well as the cladded area. It takes the difference in distance and can, therefore, output the layer thickness. The accuracy could be better, but it gives an idea of how the thickness elapses during production.

LIsec measurement system for powder cone geometry

This is a sensor that shines a laser into the powder stream and looks at the illuminated section of the powder; this data goes into software that analyses the shape and outputs the three-dimensional distribution of the powder stream. This can help in concluding the state of the powder nozzle. Another company makes the same kind of system for rectangular spot powder cones. Both can be interesting options for VHT however, they are expensive. With the new coaxial camera that will be installed in September at VHT, this geometry can possibly be checked for different heights by using a line laser and illuminating the cone at different heights. This could allow VHT to check the powder distribution at the level of the melt pool and log the change in the powder distribution over time. For this, the prototype shown in Figure 27 was made. Together with the camera, the idea is that it can record the spot at which powder arrives.

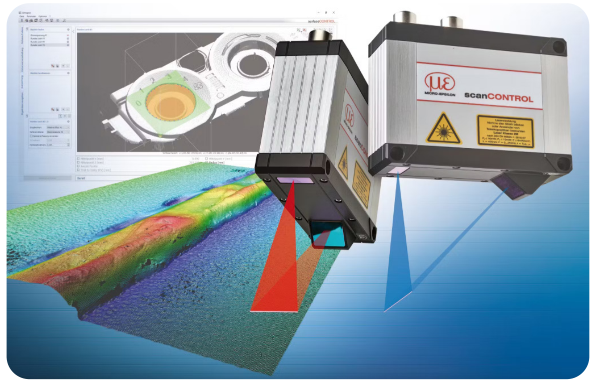


Figure 26 - LineSanner, ScanControl

More experimental monitoring tools

Acoustic emission signal

When stresses inside the substrate of the cladding layer become too great, cracks can occur. Wrong settings, like an abnormal cooling rate can cause this. When these cracks are formed, they emit a sound. In the paper [33], they built a neural network, or more specifically, two: a cladding state recognition network and a crack diagnosis network. With this sensor data and analysis, they could accurately predict 99.76% of the samples with cracks in them.

Pores and cracks can also be accurately detected using an optical microphone [34], [35]. In [36], they detected individual pores with an accuracy of 93%. This could be helpful because this is one of the main reparations that has to be done when rods are produced at VHT.

Laser-based acoustic cracking

The same idea of detecting cracks can also be done with a laser vibrometer. This points a layer at the substrates and detects the movement of the surface by reflection. Cracking in the HAZ was found using this method [37].

Clamir camera

This camera could be seen as an alternative to the Fraunhofer EMAQs camera. It is a closed-loop laser power control system for Cladding, LMD and other DED techniques
IDS camera to spot nozzle alignment problems

As can be seen, some of these sensors and add-ons were developed to detect problems stated in the section 'Faults, defects and their causes'. For example, the camera that can detect the powder cone geometry can be helpful in detecting a worn nozzle and seeing how far it has worn down.

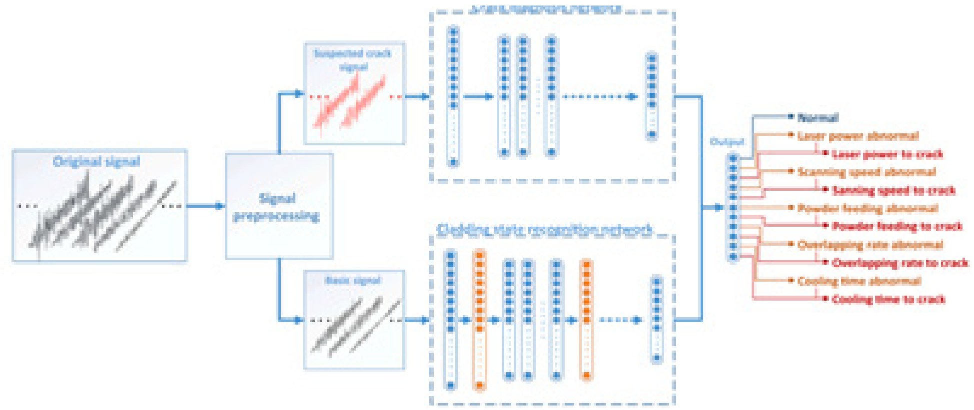


Figure 29 - Overview neural network crack detection [33]

Figure 25 - LISEC measuring device Fraunhofer

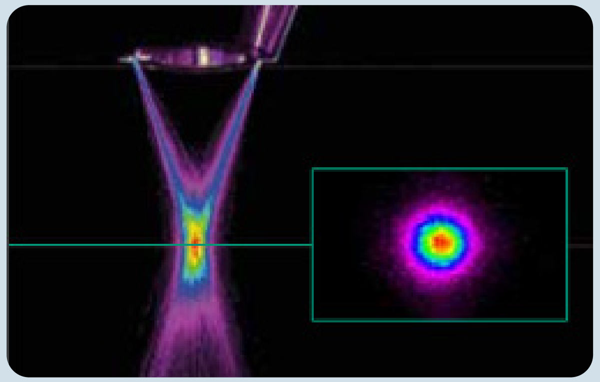


Figure 28 - Laser section LISEC device

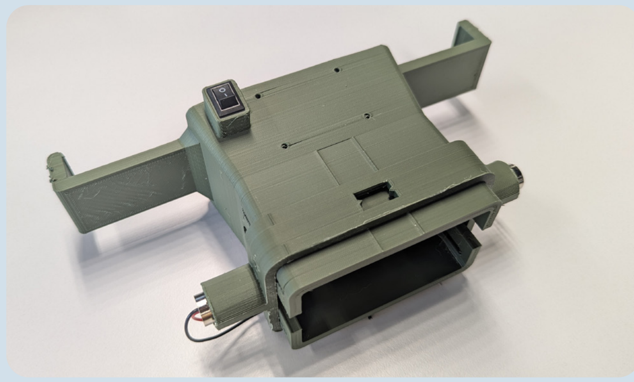


Figure 27 - Prototype for horizontal powder placement measurements

Quality monitoring

Utilizing the installed sensors and the parameters they measure entirely is crucial. Understanding how these parameters influence quality is critical. This requires a clear definition of what constitutes a good-quality cladding layer. Once there is quality information, it can be logged and used to establish relationships with the measurements taken during the process. From the research, different ways VHT can measure the quality of the layer were identified. Not all tests are done at all times on any deposited layer. Some customers require different checks and documents with their cylinders, so different checks are done for different cylinders. Logging important process data consistently and storing it for later analysis is essential for effectively comparing situations and parameters. This process is also crucial for quality control efforts.

One idea is to create a general quality score that combines all the results of the quality tests for more straightforward data analysis or to keep the data separate and use it as it is. It is always helpful to store all data because then all calculations can still be done later to get a single parameter that implies quality.

One live parameter that directly impacts one of the quality measures is the layer thickness. Tools are available to measure this thickness directly during coating. The preferred layer thickness plus the amount that will be removed during honing should be the measured thickness during coating. If this varies too much from the required thickness, the interface should communicate this and notify the operator to stop or monitor this problem.

This and other data are not easily available for the operator and should be simplified with a program that is shown on the screen. Monitoring one parameter can be a good start to see if it is technically possible and helpful for the operator. From here, more parameters could be added, and the rest of the interface could be built.

Figure 30 - Machine Metrics HMI [38]

Information and live dashboard

The goal of the live dashboard will be to make all sensor outputs accessible, combine them in one place, and choose and create the right HMI to display the data. Furthermore, the combined and stored data opens up exciting possibilities, such as training an artificial neural network (ANN). This ANN can be trained using the measured parameters from production, paving the way for enhanced data analysis and decision-making. So, creating this combined dataset will be the first step in eventually analysing the data with ANNs. Because of the machine's architecture at VHT, the sensors and camera feeds are divided into multiple systems and standalone monitoring devices. To display them all together and have control over how the information is displayed, it would be helpful if all the data were made accessible and then combined into one place. This makes the data more practical; it can now be used to create a KPI dashboard, train ANNs, or analyse the data when a fault occurs. Companies that specialise in systems that combine machine metrics and display them in an organised matter exist. A good example is the company MachineMetrics, which aims to create KPI dashboards for industrial machines. An example of such a dashboard can be found in Figure 30.

Neural network process health indicator

It can be helpful to look into Artificial Neural Networks to support or improve the monitoring of processes. The functionality and use of neural networks are ever-expanding and are proving that they could help many processes. There are already some applications where ANNs are successfully used:

Like a paper where they created an ANN for tool wear monitoring on a milling machine with the help of a microphone, a dull tool could be detected [39] Also, it has already been used with laser cladding in the estimation of layer height, which has resulted in accurate results [40]. ANN is already used to optimise general parameters [41], surface roughness [42], and dilution rate optimisation [43]. It can also be used to estimate micro-hardness. So, it can be used for optimisation, for example, using the input parameters of the process and the measured data of the process to come up with better input values. But this makes it reasonable to assume that it can also be used to create an indicator of the process's health, which can help indicate to the operator when attention is required or changes in setting are needed. Or, eventually, have this ANN control the process to create the most optimal layer.

For this to work you need a lot of data that is classified with the desired output that you want the model to give, so when you want to predict the surface roughness from weld pool images. You need in the order of 5000 images with a surface roughness value coupled to it to train and test the model. This can be done by purposely creating correct and incorrect welds together with the needed images. These images are then classified as the correct welds and the incorrect welds. The ANN trained with this data can then view similar images and guess if the image should belong in the good or bad category. In this way, a system is created that can classify wether the process is correct. A trained operator is also able to see these problems however this needs continuous attention.

The idea of using an ANN to estimate the quality of a weld is already explored, and working prototypes were made. In Figure 31, two cladding welds are shown that contain defects. In B and D, the same welds are shown, but the data of the ANN during production is laid over the welds. As a result, one can see that the marked defects are also the places the ANN detected as being an incorrect process.

The costs are low to implement; open-source software is rapidly approaching the same capabilities and quality as big players like OpenAI and Google Bard (now Gemini). For example, an open-source LLM model Vicuna-13B was trained for $300 and when tests were done it reached 92% of GTP4 its score while Bard only scored 93% [45]. Also, a custom-trained model is needed to recognise the quality of the process. This is also an area that open-source tools are more than capable of. So the model would cost the working hours of an expert and training time. This price would be easily justified if it can improve the process and prevent quality problems.

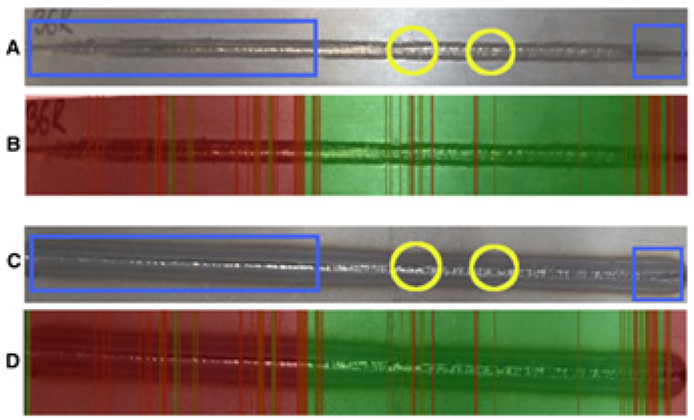


Figure 31 - Result of an ANN on detecting problems [44]

05

Human interaction research

Research into the human interaction with the machine will help make good use of the research done about the process and ways to monitor it. Information describing the optimal interaction between the operator and the machine will help answer sub-questions 5 and 8. The sensors and measured parameters could indicate problems, but if they are not communicated well to the machine's operator, the problem will not be solved. This is why this chapter is about designing the dashboards in a way that is understandable and intuitive.
During the design, consideration should be given to the ways the different parties interact with the machine and how to display information to them. Also, the different users have different goals when looking for information. In this chapter, human interaction with machines like at VHT is explored.

A new way of thinking

In production, it helps when workers are seen less as spectators and more as active players in the process [44]. This begs the question of whether the method of systematically writing down all the steps an operator has to perform in a way that no thinking is required, is the way to go. Or that it is wiser to give the operators a more profound understanding of the process and teach them why specific parameters should be like this, then still communicate the correct parameters but also the freedom (within a range) to change them if they notice something happening. For this, there is a need to think of and create tools that help an operator perform the task in a way that makes the process more stable and reduces the occurrence of faults. This could increase motivation and the detection of problems. Automation and the use of ANNs will do the opposite, so it could be helpful to keep in mind how this influences the involvement and motivation of operators.

Learning ways

To create the tool that has to learn and teach (new) operators the workings of the machine and the process they would have to control, there should be looked at how to present information in the most effective way possible. There is a lot of research into different learning styles. The term refers to the concept that different people prefer other ways of getting to know information. Learning styles that are mostly named are visual, Kinaesthetic and auditory learning styles [47], [48]. Visual is the style in which people prefer visual information, such as pictures, reading, animations, demonstrations, and videos. Kinaesthetic is the style in which people prefer to take the hands-on approach and learn by doing. Moreover, in auditory learning styles, people prefer to hear the information being explained to them. In the educational field, big industries have been built around creating instructions that fit one's preference. However, recent papers found that most research surrounding this idea is lacking, and there is no proof that adapting the information to individual preferences will help with performance [47], [49].

There is, however, a difference between the styles; in the visual learning style, students scored higher on reading and listening than auditory learners. It is even stated that an auditory learning style preference can reflect difficulty in learning or failure in becoming proficient [47] and that they can benefit from information in their non-preferred format. So, they conclude that the limited educational resources would be better used for educational practices with a solid evidence base [49]. One of those is the idea that people with higher abilities fare better in an unstructured learning environment, and people with lower abilities perform better with very structured learning information [47]. Another is that people with an internal locus of control about learning fare better in an unstructured environment, and people with an external locus of control better in a structured learning environment. However, there are still contradictory results in the research on these two topics, making it a complex topic [47]. They add that the best learning style probably depends on what has to be learned. If you want to teach writing, the focus should be more verbal; if geometry has to be taught, visuals probably work best. So, it seems best if the subject matter is taught in a realistic way that fits the matter rather than changing it to a preferred format. The interaction with the machine and the resulting process the operators have is a combination of visual and numerical information. Heat maps, live camera views and changing values are the information they must interact with and understand daily. Making graphical representations from complex data can, however, make topics more straightforward. In a paper where they review the benefits and value of graphical displays in learning, they summarize theoretical frameworks and the following design principles that can increase the performance of the student; see Figure 32 [50]. Here, the emphasis is on combining the graphical information with information (text), which is the targeted information. An example of where graphics were used to teach a complex topic was a paper called "Interactive, Browser-Based Graphics to Visualize Complex Data in Education of Biomedical Sciences for Veterinary Students", " 71% of the students affirmed that interactive graphics led to an increased interest for the presented contents and 76% expressed the wish to get taught more topics with interactive graphics. [51]" The increased interest and motivation can have a significant positive impact on learning outcomes [52]. Concluding, the best way of teaching new complex topics depends on the ability of the student and the quality and structure of the information. Using graphics in combination with small explanatory texts and interactivity can positively benefit learning outcomes. Moreover, the format of the information should fit the matter that is taught. For the dashboard, this means that it should represent reality as much as possible; also, to make learning from the dashboard accessible for everyone, it should be designed in a structured way.

Theoretical framework	Design principles
Dual coding	–Graphical displays should address the goal of the task and make target information salient to the viewers –Graphical displays are not effective without explanations that guide learners to observe key details, especially when they are intended for low-knowledge students –Graphical displays should be spatially and timely coordinated with text to minimize cognitive load –Explanations to displays are more effective when provided in auditory narration
Visual argument	–Effective graphical displays are designed based on Gestalt principles of perceptual organization. This minimizes cognitive processing and allows viewers to perceive relations or data patterns and trends using visual perception mechanisms
Conjoint retention	–Maps that are used as adjunct displays for factual learning are more effective when presented before the text (or narration)

Figure 32 - Theoretical framework and design principles [50]

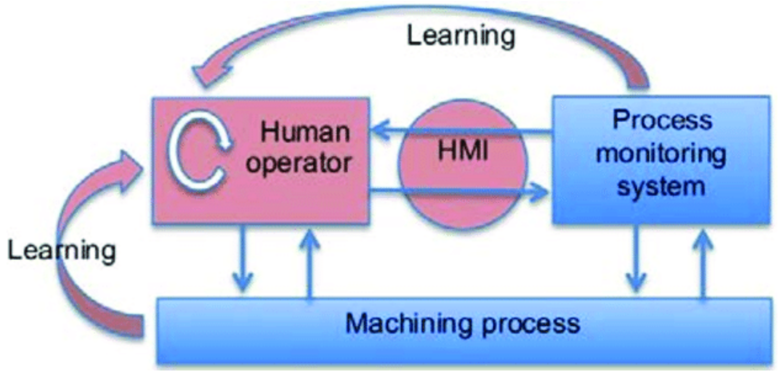


Figure 33 - Learning from processes [39]

Design for learning

When designing an environment for learning, one should consider how people learn. Julie Dirksen's book, "Design For How People Learn" [53], offers good suggestions for designing learning tools. The following paragraphs discuss a few. It helps to compartmentalize information so it becomes manageable to process. For example, when writing out a procedure, chunk the information into parts that belong to each other. This will help the learner focus on a single section at a time. Supply information in the same environment as it should be remembered, as this helps with recalling the information when located in the same environment. So, information about a certain type of machine should be learned in the environment in which the machine will be used. If tasks should be performed under a certain pressure (e.g., making decisions about stopping or not stopping a machine), you can emulate this during training to match the emotional aspect of the real-life situation. If the information is retrieved from the brain, think about what should then be done with it. Does the person only need to recognize the information or recall the information themselves? It is important to recognize and recall information in the supply of information. Make a story and couple this with the learning goal, this can interest the reader and so benefit learning. Conditioned memory, procedural memory, and muscle memory are critical for performing tasks efficiently and automatically [53]. Conditioned memory involves learned responses to specific stimuli, like reacting to an alarm. Procedural memory is the unconscious knowledge of how to do things, such as typing or riding a bike. Muscle memory stores physical actions through repetition, allowing us to execute tasks smoothly without thinking. Together, these memory types enable quick reactions and performance in familiar situations. Repetition, repetition, already told the importance of repetition? Repeatedly learning a piece of information is the best way to store it in the brain's long-term memory. But do it in multiple contexts and in smart ways so you do not remember it just because you repeated it. People struggle to do an action when the action is now, but the consequences are later. So if it is easier to do the task in another way now and the consequences are not clear or delayed, the less optimal solution is chosen more easily. A real-life example of this at VHT is not removing an old powder tube correctly because this is the easier option, but later, this resulted in an old tube being mistakenly connected and breaking due to overuse. The consequence was not clear and delayed, so the easier option was chosen. Change is hard, so any changes should be able to be implemented easily by the user. Also, there should be an explanation, of why it is done, so the motivation will be there to help with the change. Together, these tips on how to design for learning can be used while making the dashboard. Ensure the process of changing to the new dashboard is as easy as possible, as change is hard. Give information about the dashboard in the same environment. Communicate the information in chunks ordered with information of the same type. Finally, repeat the information and make clear why it has changed, what is better about it, and what the consequences will be when the new methods or dashboards are used.

Nature of human errors

Human error is a failure that occurs but is not deliberate, like a violation, where a person deviates from a rule or procedure [54]. By keeping performance-influencing factors in mind, you can pro-actively recognize and address them, empowering you to maintain control over the situation.

Types of errors

Slips and lapses can occur. Slips can occur when a wrong button is pressed, or a wrong value is read. Lapses can occur when someone forgets to close a door or remove an item from the machine. Mistakes include errors in judgment and decision-making, where a person believes they are doing the right thing but actually are doing the wrong thing. Violations: are intentional deviations from a rule or procedure however they are usually not done with malicious intent (sabotage). Often occurs when a procedure or equipment is poorly designed [54].

Human error management can be done in multiple ways and using multiple strategies. One strategy is to increase detection, explain the rationale behind procedures/rules, increase training, redesign procedures, and keep looking at why the mistakes were made. Checks like "Has the door been closed?" can be incorporated into the system to prevent lapses. Asking for confirmation while performing a critical action can help with slips. Better training solves mistakes, and when violations occur, the design of the procedures or system must be critically reviewed. Common pitfalls during design are found in Figure 34.

- Treat operators as if they are superhuman, able to intervene heroically in emergencies.
- Assume that an operator will always be present, detect a problem and immediately take appropriate action.
- Assume that people will always follow procedures.
- Rely on operators being well-trained, when it is not clear how the training provided relates to accident prevention or control.
- Rely on training to effectively tackle slips/lapses.
- State that operators are highly motivated and thus not prone to unintentional failures or deliberate violations.
- Ignore the human component completely and failing to discuss human performance at all in risk assessments.
- Inappropriately apply techniques, such as detailing every task on site and therefore losing sight of targeting resources where they will be most effective.
- In quantitative risk assessment, provide precise probabilities of human failure (usually indicating very low chance of failure) without documenting assumptions/data sources.

Figure 34 - Common pitfalls [54]

Design on Gestalt principles

These are the principles of how humans perceive the world. 'Gestalt' means form, and the principles describe how humans make sense of a visual field [55]. Figure/ground relationships are important, sometimes called 'positive' and 'negative' spaces. A discontinuity in the 'background' creates a Figure. So this means that something different from the bulk of information will stand out. This can be done with shape, colour and size. "Gestalt principles influence hierarchy, informational grouping, and readability." - Mia Cinelli [55]

In general, there are six main Gestalt principles, "similarity, continuation, closure, proximity, Figure/ ground, and symmetry and order (also known as Prägnanz)"[55] However more can be found so the list sometimes counts up to 12. These principles can be important when designing an user interface or when you want to structure and show information that is quickly understood. This can be helpful for the tools the operator will interact with. The six main ones will be described quickly.

Similarity: When objects share superficial characteristics like colour shape or size, humans will perceive them as grouped. This can be found back in design guidelines and is something that can be used to couple information that is connected to each other.

Continuation: When a group of elements seems to follow a path in one particular direction, our brains do not see them as separate objects, but our eyes will follow the direction. Even if other objects cross the path or it is shortly interrupted, this line is still followed.

Closure: Humans prefer complete forms and shapes this is why they will automatically fill in the gaps in between elements. This makes it so humans see the complete image, the creative use of shapes to create a whole can be pleasing and be used to gain users admiration.

Proximity: If elements are placed closer together, humans will group them together and separate them from the other groups or elements. This can be used to group things that belong together literally or that the designer wants to be viewed as related to each other.

Figure/ground: Humans like to know things for certain and dislike uncertainty, so humans look for solid and stable items. That's why humans mostly see the 'foreground' first. By making objects stand out, dark objects on a light background, users can be guided in their work and so the cognitive load is reduced. Prägnanz: We as humans have limited attention and processing capacity of visual stimuli. Our brains will, therefore, simplify the constant bombardments of stimuli. This simplification of complexity helps us to see order and regularity in the world around us.

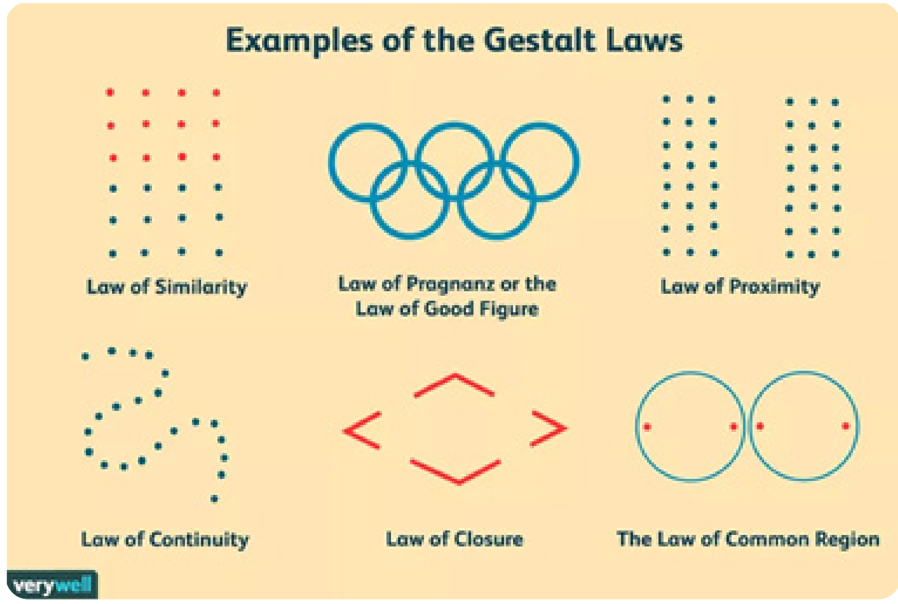


Figure 35 - Examples of Gestalt laws [55]

HMI Design

When all the correct and valuable data for the process is collected and logged, a monitoring screen that communicates the correct information to the operator can be created. The screen(s) that will be made will, therefore, not be the actual HMI where the machine is controlled, as this is another PC with software that cannot be changed, and for the goal of creating more insight, it is also not helpful to change. The three screens that are connected to the monitoring software and laser control software are the screens that can be used to display the sensor data in an better way that will improve process insight. To do this, knowledge about how to display information intuitively and helpfully is needed. Books and academic papers can provide some ideas and systems for doing this correctly. The creation of an HMI should be an iterative process, a loop of design, prototyping, user testing and evaluation [56]. So, the outcome of this research, design, and user test should be taken into account. With these outcomes, a better version is created until a suitable interface is found.

From the book "Design Tips to Create a More Effective HMI"[57], multiple good suggestions could be learned to take into account during design:

- Create a storyboard

This storyboard can describe scenarios that are likely to happen, in this way there can be tested how, in certain situations the operators have to use the interface and if this can be done easily on the HMI. This is mostly done with complex interfaces that require extensive input.

- Talk to operators and get their feedback

This sounds like a very logical step but this is something that can be forgotten when an external company needs to make something for workplace they have never been. It helps to know their perspective of what the software needs to be and what the operators need.

- Use colours and animations with sense

Colours can be a good way to group elements and connect them, also it can be used to evoke a certain association e.g. green is good. However, it should not become a chaotic disco of colours. The same can be said about an animation of for example a valve closing. This can add clearness to what is happening however the animation should not become distracting.

- Add graphics

A picture says more than a 1000 words.

- Beware of pop-ups

They can be distracting.

- Offer situational awareness

Moreover, it is essential to identify the critical information that should be locked to a specific screen area for constant accessibility, such as "traffic light" indicators. While knowing the current temperature might be sufficient in some cases, presenting a trend graph could empower operators to anticipate and prevent potential problems. However, it's important not to assume that more information is always beneficial. Instead, focus on understanding what information is critical, its quality, and how it should be interpreted. Equally important is knowing the level of domain expertise of the HMI users. This insight helps determine the most relevant details to explain and include, ensuring that users can make informed, accurate decisions without overwhelming them with unnecessary data.

Data visualisation

Data visualization plays a crucial role in presenting complex information clearly and efficiently. Regardless of the software used, the choice of graphs or charts should align with the type of data being represented [59]. For instance, time series data, status indicators, and position-based data require different visualization techniques. Statistical Process Control (SPC) is a key tool in data analysis, often used to ensure that a process is within a specific quality range [70]. When means or other data points fall outside of the control limits, or do so repeatedly, warnings can be issued, highlighting the importance of SPC in ensuring a product is produced within a specific quality range.

Graphs and charts are fundamental tools in the visualization of data. It is creating ways to communicate data in a digestible and comprehensible manner. An extensive set of numbers can be communicated in a small space [60]. However, the formatting of these graphs and charts can influence how the user interprets the data. Communicating the data aims to give the user a realistic overview of what is happening in reality. This can mean that it is not helpful to scale the axis in a way that allows the user to see the sensor noise, as this does not say anything about the process and can only confuse the user and make them spot false trends. A mean can be used to mitigate this noise. There are a few ways in which the perception of data can change because of how it is visualized. Figure 36 provides a comprehensive overview of various ways to design graphs and tables, categorized for easy reference. This figure serves as a resource for looking at which ways certain types of data could be shown.

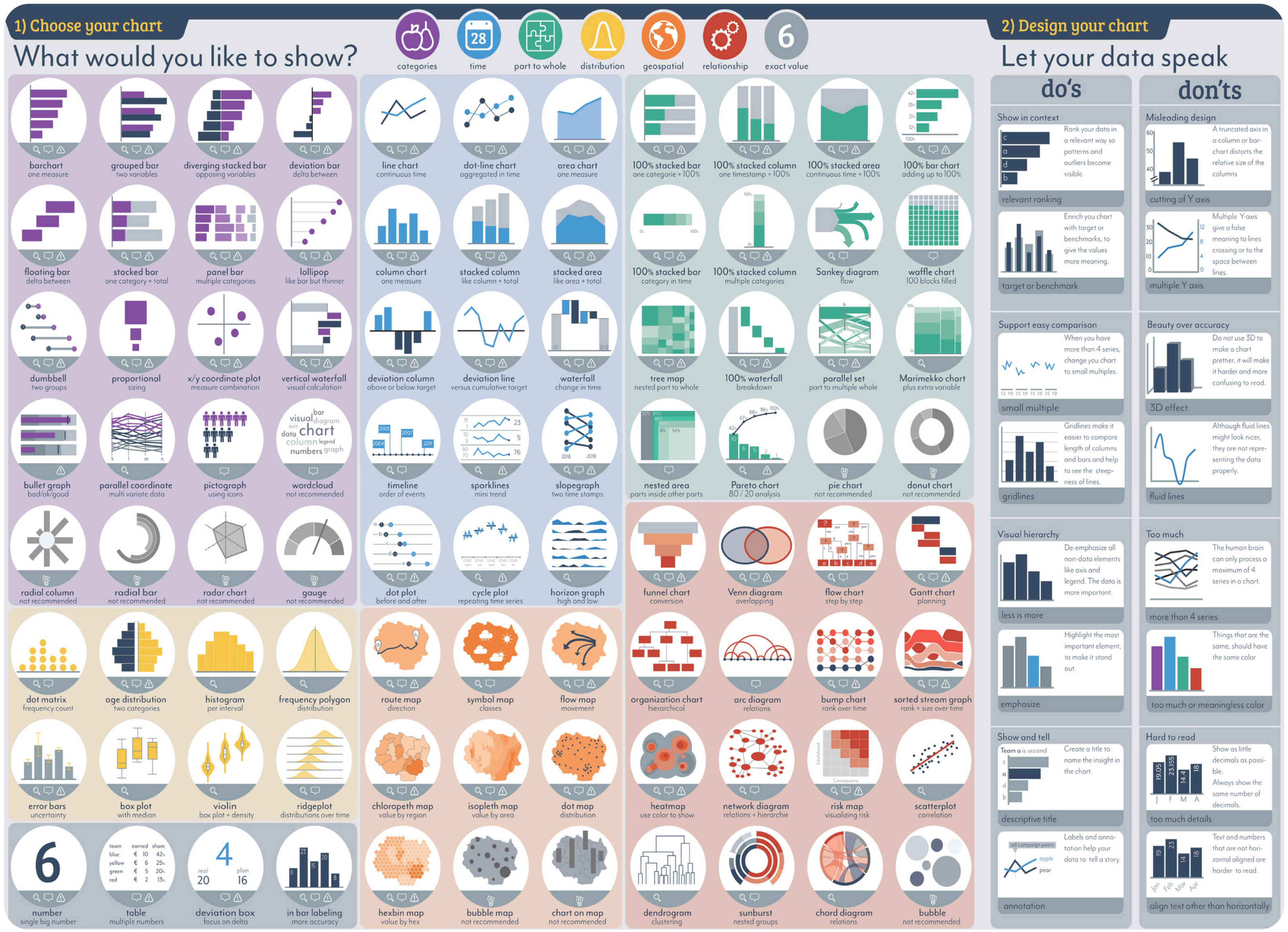


Figure 36 - Visualisation options [chart.guide], [58]

Type of visualisation

There are many charts and graphs, each meant to communicate data in a specific way. Bar charts, line graphs, pie charts, and scatter plots each emphasise different aspects of the data. A line graph is helpful for illustrating trends over time because of its continuous nature. A scatter plot is better for plotting two columns against each other to find correlations. Lastly, a bar chart is more helpful when comparing different categories. Misalignment between data characteristics and graph type can confuse users. Using a bar chart to visualise a temperature can obscure trends and may not be as helpful as using a line graph.

Scale of axis

Scaling was one of the issues of the interface at VHT. In time series data scaling, the X-axis will influence the amount of history and data that is shown. Zooming in on the Y-axis will increase the deviations and trends in the data; however, zooming in too much can create data that does not mean anything because the deviations are so minor that it does not matter for the process or only sensor noise is shown. In Grafana, there is the option to set soft limits, limits and an auto-scaling function. The latter is helpful for always having all the data in view. However, limits can be set to make better use of space and prevent outliers in the data from messing up the scaling. There can be set certain minima in the dashboard to keep the graph zoomed in enough but with a flexible upper limit. Configuring these settings correctly will help maintain a readable interface where the user does not have to zoom too much to see the required information.

Use of colour and Contrast

Giving elements in the interface the same colour can give the impression that they belong together. This can be helpful in making differentiation between different data streams, or by giving, for example, all temperature values the same colour, it can group the temperature data coming in. Contrast is helpful in letting elements and lines stand out. Elements with more Contrast will be noticed quicker and more clearly, so with this, the importance or the users attention is steered.

Other important aspects of graphs can be to include grid-lines, legends and labels to make the graph clearer and better readable. Another important setting that influences how the data looks is how the data points are connected. This can be done by a straight line until the net data point, rounded lines, or steps up and down. This is called line interpolation and can change how data looks.

Disconnect time

If a data stream is interrupted for too long or no measurements are done, for example, when the machine is off, no new data points are coming in. If then later a point comes in, a line can be drawn to the new point. However, this gives the impression that something happened between the data points; this is false, so it is helpful to set a maximum time for which data points are connected to each other. In Grafana, this was usually set to 10 seconds because this quickly shows if there are any gaps in the data, as there should be a data point every second at the minimum from each metric.

06

Product and requirements

In the problem statement, the issues with the cladding machine at van Halteren Technologies are described. Research was done to get a better understanding of the process, the ways it is monitored and the interaction with the user. This research will now be used to build dashboards for van Halteren technologies with the aim of creating more insight into the process and the ability to predict the quality of the layer better during production. Testing the dashboards and exploring the newly collected data was done continuously

Stakeholders and users

Together with the research on the process of laser cladding and the human interactions involved, an actual product will be delivered to VHT. This product will be a way to store and display live and historical data. These dashboards and data will provide VHT with new insight into the process. A back-end and server are set up to make this data storage possible. Also, dashboards will be available to any stakeholder of the machine. This means that multiple stakeholders will interact with and be influenced by the product and deliverables. The following analysis was done to give an overview of the stakeholders, users, and their interests/ influence.

Stakeholder	Role	Interest
Operator	Monitoring the cladding machine and the set up of the rods	Access to accurate and clear live process information to judge the process
Process Engineer	Managing the laser cladding process and its production	The stable production of new coatings without any NCR's
Quality control	Guards the quality of the produced coatings by quality checks	Only deliver coatings of the highest quality
IT department	Maintenance of the back-end of the interface (database, network, hardware)	Having a safe and stable IT system
Development Engineer	Keep VHT up-to-date with all new technology developments	Ensuring the process can benefit from new technologies.
VHT	Managing company	Providing great quality coatings for a good price
Customers	Buyers of coated product	Receiving a coated rod according to specifications without defects and of the highest quality.
Notified body (3th party)	Checking standards and procedures	Making sure all parameters are up to the (ISO) standards

Stakeholders benefit of new dashboard

Process engineer

Manages all facets of the process, from the machine to its setting and the recipes that will be made. Directs the operator on what to do and how to do it. A new dashboard will allow users to check how the process is going in real-time and lookup data afterwards to spot problems and check quality.

Operator

The operator, whose main task is to prepare for cladding and ensure it proceeds as directed by the process engineer, will benefit significantly from the new dashboard. It will provide them with a comprehensive overview and insight into the live process, enhancing their monitoring and control.

Quality control

Performs quality checks after production and documents all the deviations in the process. If problems are found, analysis is done to find the cause. Quality control can benefit from the dashboard if it can show important process data.

VHT

The VHT will benefit from the new dashboard in several ways. It will reduce the time required to investigate problems, increase insight into the LC process, and potentially improve product quality, thereby enhancing their ability to sell a better product.

Requirements

The format for this requirement list was based on the format specified in the 'IEEE Guide for Developing System Requirements Specifications' [61]. This list of requirements was created after a meeting with most of the stakeholders involved in laser cladding at VHT and, most importantly, the process engineer who will be the primary user of the dashboard. Information was obtained from the operator during observation and when asking questions during production. Before the meeting, a brainstorming board was created, which can be found in the appendix under "Brainstorm meeting." A list of possible requirements was also created before this meeting, but they were hidden on the board so the participants were not steered by seeing those ideas. Later in the meeting, to keep the meeting going, some of the requirements and ideas made beforehand were discussed.

Purpose of database and interfaces

The purpose of the database and interfaces is to log all available data surrounding the LC machine in a way that allows for real-time data retrieval and post-application access. The interfaces are designed to facilitate quick and easy visualization of the available data and enable comparative analyses. This system is intended to provide a high level of process insight.

Scope

The interfaces and required back-end for the LC machine at VHT are included in this project's scope. The interface before the project consisted of five screens and software running on the screens. A database was already in use and is included in the scope. All data communications inside the cladding machine are also included. The HMI of Fraunhofer that directly controls the machine is excluded as this interface cannot be changed by VHT and is performing as expected.

Constraints

Time:
The project, including research and writing this thesis, must be completed in eight months. The IT infrastructure is an essential part of creating an interface that can be used for (user) testing. Arranging the setup of this infrastructure can take some time. Only after the infrastructure has been set up will it be possible to build the interface. Only then will the correct data format of the arriving data be known.

Hardware:
The machine has been expanded with multiple sensors, computers, and devices. Adding sensors and hardware is possible; however, this takes time and a good business plan. So, significant expenses are probably not possible during the project. During the project, a new PC with two new cameras was installed, and in the near future, a new coaxial camera for alignment purposes will be installed.

Safety:
At all times and tests, safety must be guaranteed.

Capabilities, conditions, and constraints

The design of the dashboard will depend on the needed capabilities, conditions, and constraints imposed by the software, costs, or infrastructure. As the dashboard will need to display live data as well as historical data, different dashboards will be made.

Database:
The database has to:
- Store all time-series data that the LC machine can output
- Be accessible within VHT-network
- Be made for time-series data and have efficient storage
- Have low latency when sending and receiving data
- Work with the to-be-designed interfaces as well as the already-used software (PowerBI, Matlab, Exel)
- Pose no significant risks to the security of the machine inside the network
- Have access to all data! (Needs time and contact with Fraunhofer)

Preferences:
- The system should not require licenses or software that costs more than 200 Euro's a year
- Existing hardware can be used or extra hardware below <1000 Euro's
- Data is transferred with as few intermediate steps as possible

Historical display
The user should be able to:
- Select data specific to one rod and the specific layers on the rod
- Select by type of coating
- Compare different rods to each other for the key performance indicators
- View the data in an appropriate visual format
- Load the dashboard in less than 5 seconds (including aggregations and calculations)
- The interface can be accessed by anyone in the network

Goal: To make the process of looking up the data for analysis a 10-second task instead of an hour.

Real-time analytical interface
The user should be able to:
- View the data that is produced by the sensors in real-time (no more than 5 seconds latency)
- View the melt pool temperature as quickly as the Lompoc software does
- View Xiris camera values as the original software has only a basic graph function.

Preference:
- Accessible within the whole network
- Use Grafana live*: this ingests live data without storing it in the database first which takes up to two seconds.

Real-time Traffic light
- The user should have access to the same information and with the same latency as the real-time display
- The operator should be able to react to underlying problems by having a traffic light that indicates the state of the sub-processes
- The interface should contain no more than six main indicators
- For visibility, the indicators should be able to be viewed on the same screen or next to the camera view.
- Have logic behind it that detects problems and the 'health' of the process

Preference:
- Accessible within the whole network
- Have one main indicator that has three options: fine continue, ask the process engineer, and stop the process

Total configuration of the screens
The interface:
- Should display camera views of all sensors
- Should incorporate the real-time analytical dashboard as well as the traffic light dashboard
- Should have room left for Lompoc software and software of data that cannot be displayed as quickly as the original software.

Additional Options:
- Play sounds when machine starts/stops > tested and works
- Display values/graphs over pictures
- Video streams in the dashboard (emaqs, xiris)
- When connected, let PC's (xiris and emaqs) save pictures to local network location.
- Show emaqs/xiris images for selected data, e.g. time of location, or have an easy way of accessing this data.
- Have a list of what orders were made each day
- Pictures with data overlays
- Flow diagrams with data
- Log x-y position settings with the rest of the data

* All black text has been realised during this thesis

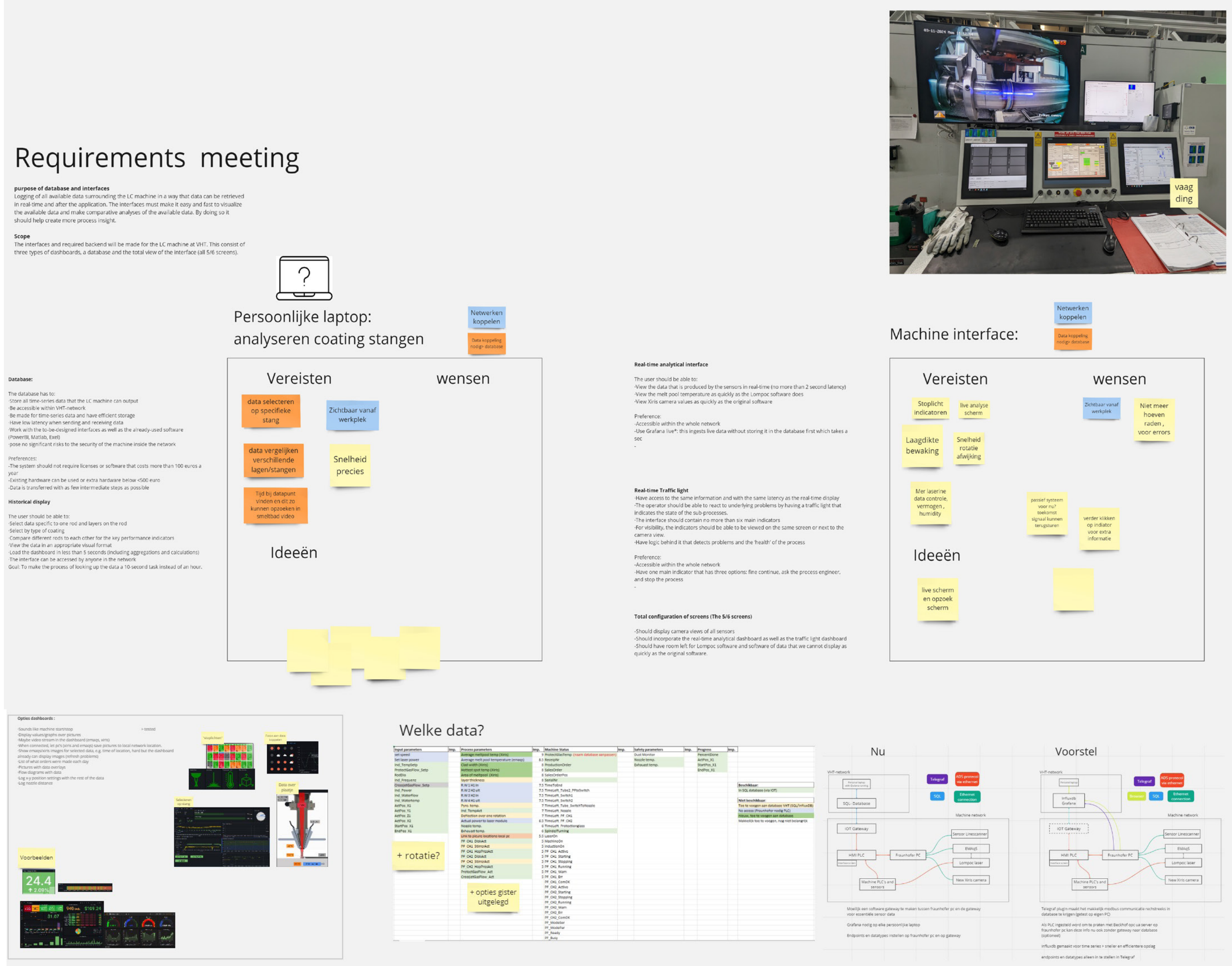


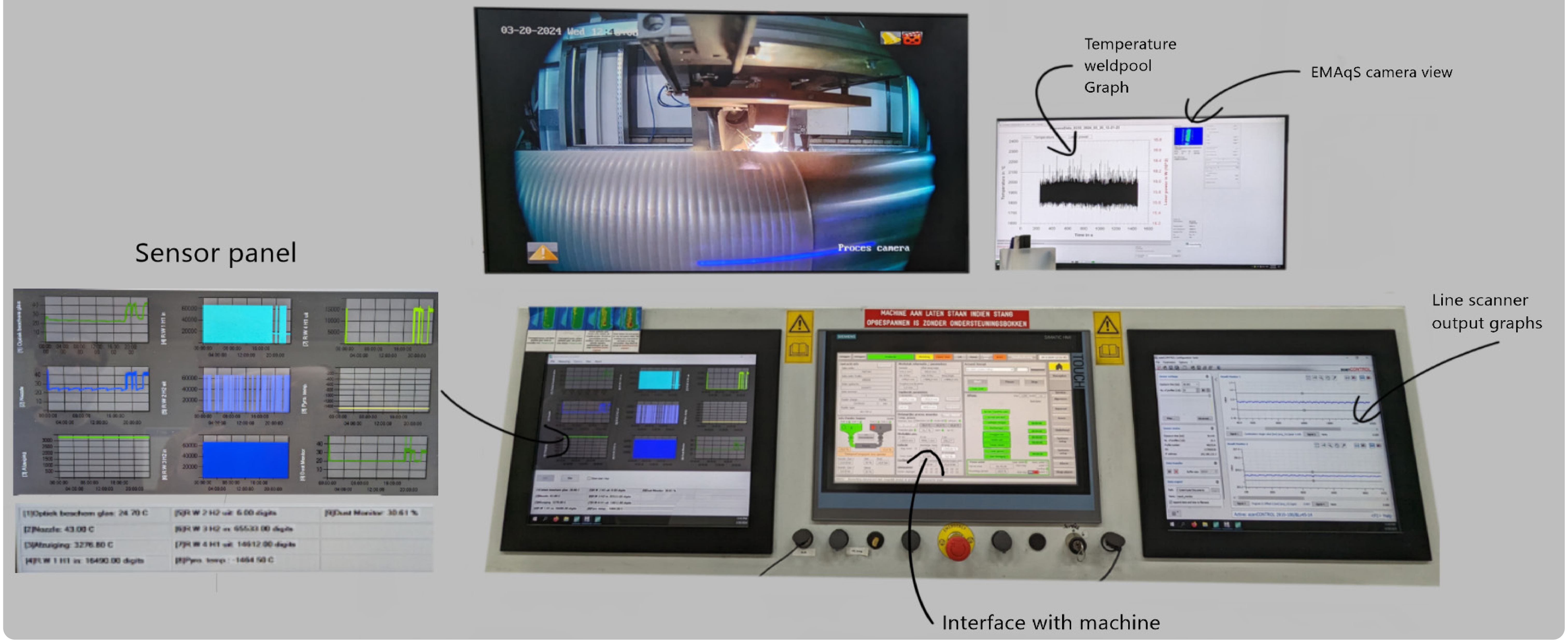
Figure 37 - Section of the Miro board used for the requirements meeting

*Grafana Live has the option to receive data directly from telegram without the step of storing the data inside the database and requesting the data later. [62] This makes it possible to create a metric on the dashboard that has a very low latency of a few hundred milliseconds.

Current interface at VHT

In the factory at VHT, the interface of the laser cladding machine has been built up out of five screens. These screens display the different information available on the machine and from the different sensors. Having five displays means having many places with information, which could be distracting, especially when they are filled with different software with their own way of visualizing the data. The following two pages will describe the interface as it was at the start of the project, describing where sensor information can be found.

Current interface



Problems with the current interface

Sensor panel (Fraunhofer)
Displays sensor data took from the PLC communications and has an update frequency of one second. Problems: It is hard to make sense of the graphs and understand what is happening with the sensor data because of scaling and false data. It does not always reset correctly, so data from the last two days could be crammed into one window. When checking this screen 2 days consecutively the graphs remained frozen and displayed the same graphs and information. This wasn't reported as a problem by the operators, meaning that they assumed the information was constant or did not look at this data to monitor the process.

Process camera (separate video system)

It gives a visual view of the process, allowing the operator to view the bead that is laid down and the spatters around the weld pool, which could indicate problems. This overview also makes it possible to see the orientation of the nozzle head in relation to the rod.

EMAQS camera view (Fraunhofer)
A view of the weld pool recorded by an NIR camera is used as one of the main indicators of a 'healthy' weld pool. Posters displaying correct and incorrect images are used to help operators judge this picture. However, it is displayed on a very small area of the screen.

Temperature weld pool graph (Fraunhofer)
There is no automatic scaling. At the machine's start-up, you can see the line moving. After a while, only new peaks are noticed, but the graph becomes almost useless. This could be solved by using one graph that shows the temperature over a longer time (3 hours) and one that gives the temperature of the past minutes.

Line scanner (Micro-Epsilon)
It measures the profile and distance of the substrate in relation to the sensor. It can be configured to measure multiple dimensions. For now, it measures the distance to the substrate (used for oscillations) and the layer thickness. There are questions about the accuracy of this layer thickness measurement, as there is much noise in these measurements.

Interface with machine (Fraunhofer system)
This screen runs and controls the software that directs the LC machine. It will be hard to change because it is maintained by Fraunhofer and can only be changed upon request, so it will be outside of this project's scope. This screen includes some values that can be interesting to log and display/graph.

Detailed view current interface

1. Optical protection glass °C : working display, however has zooming issues
2. Powder sensor 1: working, zoom issues, particle count has no meaning
3. Powder sensor 4: working, zoom issues, particle count has no meaning
4. Nozzle °C: working display, zoom issues, can see the effect of cooling
5. Powder sensor 2: working, however displays incorrect data when not in use
6. Pyrometer °C: No display of information, however correctly value visible on the main dashboard (11), only works above 150 °C.
7. Fume extraction: steady value which can mean it's on, change to on/off or value
8. Powder sensor 3: Unusable information, but moving average changes when cladding

9. Dust monitor %: Changes from 20 to 30 percent when cladding is off and on
10. Gas flow values (l/min), Disk speed (%), Pressure (Bar)
11. Pyro meter °C, protection glass °C, protection glass %, nozzle °C, exhaust °C
12. Line scanner layer thickness and (mm): Not calibrated but working, benefits from a trend line
13. Cladded layer distance to sensor (mm): Can show oscillations in the rod
14. Process camera, good for general overview process
15. Set temperature and average temperature EMAqs window °C, scaling/zoom issues and benefits trend line or different time scales to spot trends.
16. EMAqS thermal camera, is helpful, size can be bigger, guidelines for interpretation
17. Laser, laser power and EMAqs settings

The blue rectangle includes the control interface, hard to change and is working so this screen will stay the same.

07

Setting up data collection

The current situation at VHT collects different data streams and stores them in seperate locations on the hardware at in the factory. To analyse and view this data, it must be copied to a USB stick and loaded into software. This takes a long time and does not make live dashboards possible, also the timestamps of this data do not compare. This makes it hard to find relations between data. As can be seen later in the 'explorative phase', problems and data were examined to find ways of visualisation and software that work with the data. In this section the necessary IT infrastructure and data collection software needed for the dashboards are discussed as they are essential to create working visualisations.

Data flow and system at VHT

The process data VHT wants to store and visualise is located in different programs, PC's and sensors. The sensors also have different ways of communicating and outputting their data. Any sensor has custom software that is written for that specific device/camera. It also has its own visualisation software. However, as it is best to collect all the data together and then neatly visualise it, there needs to be a way to collect and store it.

The PLCs that make the machine operational output their data in ADS format. This is how the SensorMonitor gets its data to display. However, the same network of PLCs is connected to an IOT gateway, but only some of the information the SensorMonitor displays ends up in the database. The Linescanner, EMAqS, and the new Xiris camera all have their own way of storing data. They are primarily stored in different text/.CSV files that look like Figure 41. However, some also have live output capabilities, e.g. Modbus for the Linescanner and OPC UA for the Xiris camera (when this expansion is bought). Live data transmission is preferred over parsing the log files as this can give problems with aggregating data and update frequencies. When a live data stream is used to input it directly, it can also not be forgotten to press a specific button to start logging.

Microsoft SQL Server is the software currently used for some of the PLC data at VHT; however, it is not made for real-time data and IOT devices. To have a system that can handle the sensor data quickly and supply data to a real-time monitor or other computers that later want to analyse data, different kinds of databases are better suited. Because the metrics that needs to be stored are dependent on time and relate to each other with time, a time series database is needed. It would also be helpful for the project if it could be installed on the servers that are already available. The choice of this software and database is explained in the next section.

Choice of software

During the exploration phase, different ways of visualizing the data were used. PowerBI for analysing files taken form the PC's, python and different python library's to test data processing, visualization and logic like setting limits. PowerBI was already used internally but was lacking real-time options. Python is a good option but will become complex when full dashboards will need to be created. There was looked at open source and commercial software however for the execution of this thesis it helped that no software needed to be licensed or bought. This would have imposed delays.
The decision to implement the so-called "TIG stack" Telegraf, InfluxDB, and Grafana for this project was driven by several key factors including excellent documentation, a vast array of plug-ins, and the open-source nature of the software. This combination provides a robust, scalable, and efficient solution for data collection, storage, and visualization. At the next page the choice for Telegraf, InfluxDB and Grafana is further explained.

Telegraf, as the data collection agent, emerged as the optimal choice for its lightweight and efficient design. Its capability to run on minimal resources, coupled with real-time data processing, ensures that data is promptly and accurately processed before being stored. The software supports over 200 plug-ins for input, output, processing, and aggregation, which provides significant flexibility in integrating various data sources. Additionally, the comprehensive documentation for Telegraf, including guides on custom plug-in development and integration with different systems, facilitates ease of implementation and customization, making it a reliable choice for high-throughput data collection.

InfluxDB was selected as the time-series database for its superior performance in handling high-throughput data, which is crucial for time-series data management. The database offers an easy setup process, supported by a user-friendly GUI that simplifies maintenance and administration. The extensive documentation provided by InfluxDB, covering aspects such as setup, data ingestion, querying, and administration, ensures that users can efficiently implement and manage the database.

Grafana was chosen as the visualization tool due to its flexibility and extensive integration capabilities. It supports multiple data sources, including direct integration with InfluxDB and Telegraf, which allows for seamless data visualization. Grafana's documentation is thorough, covering dashboard creation, panel customization, data source integration, user management, alerting, and plug-in development. The ability to create both basic visualizations and highly customized panels, along with a vast library of plug-ins for various data sources and advanced visualization options, made Grafana the preferred choice over alternatives such as **Kibana**.

In contrast, several alternatives were considered but ultimately not selected. **Prometheus** was recognized for its monitoring and alerting capabilities, but it was less suited for the high-performance time-series database needs that InfluxDB excels at. **TimescaleDB**, while robust, did not match InfluxDB's performance and scalability for this specific use case. **Kibana,** although a powerful visualization tool, lacked the flexibility and seamless integration offered by Grafana. Additionally, commercial solutions such as **Datadog, Splunk, KDB**, and **New Relic** were evaluated; however, their high licensing costs and reduced flexibility compared to open-source alternatives made them less desirable for this project. Lastly, **QuestDB**, despite being an open-source solution, was not selected due to its relative obscurity and the corresponding lack of comprehensive documentation, which is critical for successful implementation and maintenance.

Conclusion

Telegraf, InfluxDB, and Grafana were chosen for this project due to their great documentation, extensive plug-in support, open-source nature, scalability, performance, and integration with each other. These factors ensure a robust, flexible, and cost-effective solution for data collection, storage, and visualization, making them the ideal choice to create the dashboards.

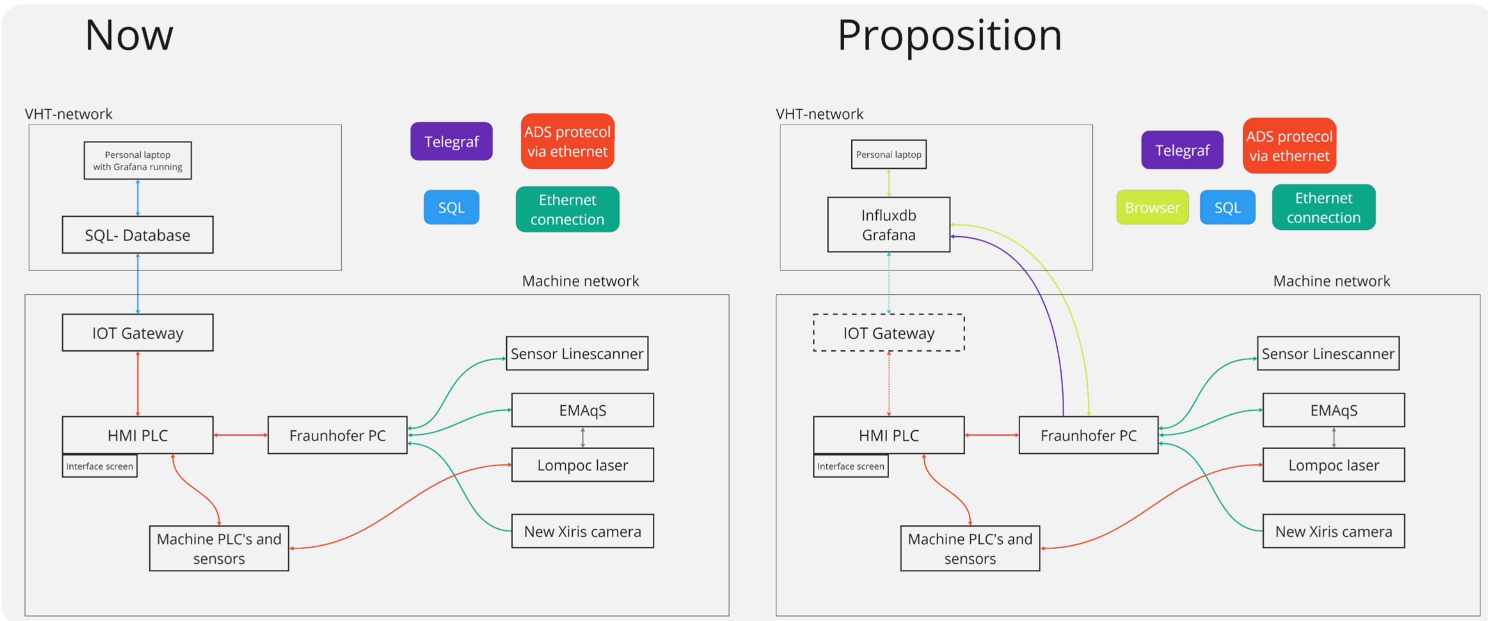


Figure 38 - IT changes and needed connections - a complete network map can be found in the Appendix

Data processing

To build a helpful database from which data can be easily selected, relations need to be added between specific data sources. In a time-series database, the different data points all relate to time, as the name implies. However, additional grouping and relations can be helpful. InfluxDB data is stored with different attributes: "_Time," "_measurement," "_Tag," and eventually the "_Field" with a "_value." These attributes are all saved in "buckets," which are different databases that can contain data. For this project, the databases: 'testing', 'CDOWAA', 'Logbook', 'Feedback' and 'quality' were made. The logbook and feedback can be filled in any way that is desired. However, the data from the sensors is input in a specific format. This format can be changed using processors, aggregators, and code inside the Telegraf configuration file. Each plug-in generally comes in as an individual'_measurement'. Tags can be added to this measurement to make the fields and values part of a particular group with the same tag. Finally, all the values get a _Time value in the form of a timestamp.

For example, Figure 39 is an excellent example of a measurement being written to InfluxDB. This line of code is generated by the Telegraf plug-in running on the machine's computers. These plug-ins relay real-time data or transform text files, as shown in Figure 40.

The line in Figure 39 inputs all the data under the measurement' line scanner', giving the data a relation with the production order and serial number. It also inputs a thickness of 1.23 and a distance of 25.1 into the database under the UNIX time in seconds 1719402654, which stands for "Wed Jun 26 2024 13:50:54. "

The challenge with the incoming data is that they all have different frequencies at which they enter Telegraf—most of the time using the UNIX time. However, for accuracy, some are in ns, like 1719402654000000000. So, the database can have multiple timestamps within the exact second or even ns. This makes it harder to say that when the position was at 130mm, the temperature was 50.4 °C because they do not have the same timestamp and originate from different measurements. Luckily, Grafana has an option to join data together by the timestamp, even when they are different. This is done by aggregating them, for example, per second, taking the means, and then joining the data together over time. This can now be plotted using the default visualisations. This is needed, for example, when plotting the temperatures against the position on the rod. In this case, the columns must be related to each other with time.

Another challenge is giving all the measurements the correct tags to be able to select the data that is produced per specific cladding session. This could be a specific production order with a serial nr and the first or second layer. There is one measurement coming out of the PLC that has this information; this field can be converted into a tag inside this measurement. Now, all these fields are classified by this tag. However, other measurements do not have this information, and the data has a different frequency. One way this can be solved is by not giving the data a tag and making Grafana plot the data from the first time a specific tag is used to the last time a specific tag is used. This works if production completely finishes one production order before the other. This is usually the case, but not every time, so it has to be done differently. The neatest way would be to give each data point those specific tags. This could be done by writing a custom processor script that processes all lines that pass it. If one of the lines contains the tag it will update the tag in a variable, if a line passes that does not contain the tag it will add the tag from the stored variable. In this way, each data point will get the right tag. This code works and is included in the Telegraf code.

Some inputs are also in-putted by log files; however, they don't have an appropriate timestamp column. However, they have a column showing the time in ms since the start. From these files, the file-name had to be converted into UNIX time. To this time, the "Time in ms" column had to be added, which then has to be converted back to a timestamp format influx could read.

These processes and other conversions were needed to create the code and file that correctly inputs all data into the DB.
Figure 39 shows a snippet of this configuration file, and the whole code, including explanations, is located in the appendix under "Telegraf code".

```
linescanner,productionorder="1234567890",serialnr=1 thickness=1.23,distance=25.1 1719402654
```

Figure 39 - Line protocol of how each row of data should be inserted into the database


```
Time in ms;Optiek beschem glas;Nozzle;Afzuiging;R.W 1 H1 in;R.W 2 H2 uit;R.W 3 H2 in;R.W 4 H1 uit;Pyro. temp.;Dust Monitor;
0000000.0;028.30;048.10;3276.80;16910.00;003.00;65530.00;10371.00;-1464.50;020.61;
0001000.7;029.70;024.00;3276.80;17051.00;005.00;65533.00;12297.00;-1464.50;020.58;
0002000.7;029.70;024.00;3276.80;17047.00;004.00;65531.00;11928.00;-1464.50;020.74;
0003001.4;029.70;024.10;3276.80;17064.00;004.00;65518.00;10948.00;-1464.50;020.28;
0004002.4;029.70;024.00;3276.80;16957.00;65534.00;65515.00;10540.00;-1464.50;020.55;
0005003.1;029.70;024.00;3276.80;17039.00;004.00;65532.00;10405.00;-1464.50;020.34;
0006003.7;029.60;025.20;3276.80;17018.00;002.00;65529.00;10351.00;-1464.50;028.42;
0007004.6;029.70;032.30;3276.80;17049.00;004.00;65533.00;10279.00;-1464.50;027.91;
0008005.7;029.70;035.70;3276.80;16974.00;004.00;004.00;10507.00;-1464.50;028.54;
0009005.4;029.70;038.40;3276.80;17008.00;005.00;000.00;10407.00;-1464.50;028.63;
```

Figure 41 - Raw process data stored on the computers and logged in real-time

```
[[inputs.modbus]]
  ## Connection Configuration
  name = "Linescanner_modbus"  # Device name
  slave_id = 1          # Slave ID of the Modbus device
  timeout = "500ms"       # Timeout for each request

  # TCP connection via Modbus/TCP
  controller = "tcp://192.168.210.5:502"

  ## Define the configuration schema
  configuration_type = "register"

  ## Register Configuration

  ## Analog Variables, Input Registers, and Holding Registers
  input_registers = [
    { name = "Laagdiktex", byte_order = "ABCD",   data_type = "UINT32",   scale=1.0, address = [0, 1]},
    { name = "Laagdikte2x", byte_order = "ABCD",   data_type = "UINT32",   scale=1.0, address = [2, 3]},
    { name = "Afstandx", byte_order = "AB",   data_type = "UINT16",   scale=1.0, address = [4]},
    { name = "Tempx", byte_order = "AB",   data_type = "UINT16",   scale=1.0, address = [5]},
  ]

[[processors.starlark]]
  namepass = ["Linescanner_modbus"]
  source = '''
def apply(metric):
      x = metric.fields['Tempx']
      y = 0.1 * x - 273.10
      metric.fields['Temp'] = y
      return metric
  '''
[[processors.starlark]]
  namepass = ["Linescanner_modbus"]
  source = '''
def apply(metric):
      x = metric.fields['Afstandx']
      y = (x - 32768)*0.005+250 #from scancontrol manual
      metric.fields['Afstand'] = y
      return metric
  '''
[[processors.starlark]]
  namepass = ["Linescanner_modbus"]
```

Figure 40 - Code snippet of one of the Telegraf inputs

08 Explorative phase

Testing the dashboards and exploring the newly collected data was done continuously throughout the project. This was a choice as many unexpected problems and situations happen during production. To make the product fit the production environment the best, the solutions to the described problems will be implemented in the dashboards.
At the start of this phase the software was not chosen yet so data is explored with the help of programs like PowerBI, Python, Exel, SQL and eventually grafana.
This chapter will show all the testing done throughout the project and explain some problems found during production that need to be detected in the future.

Layer thickness sensor

At the beginning of this phase, the layer thickness sensor was interesting to start exploring with. This is because it has well-documented software with multiple data outputs. This made it possible to start testing if data transmission to a database was even possible to a database. The Linescanner outputting the layer thickness needs to be calibrated to work correctly; this has to be done with a manually measured value. This value now has to be compared to the sensor value and a correction has to be input into the system. This process can be made easier in the new dashboard by using the uncalibrated value in the database and programming this interface in a way that after the first bead is laid down, it automatically averages the value, and then the operator can fill in the measured average thickness and the program calculates the difference and corrects for it. Making the calibration process more manageable for the operator and so compliance with using this sensor correctly can be improved. Because on multiple occasions, the sensor was not calibrated. To test having control limits and the calibration method, a Python program was created that used actual data to simulate how this could look. Also, this was the first test of an indicator that could turn red if the value was outside its control limits.

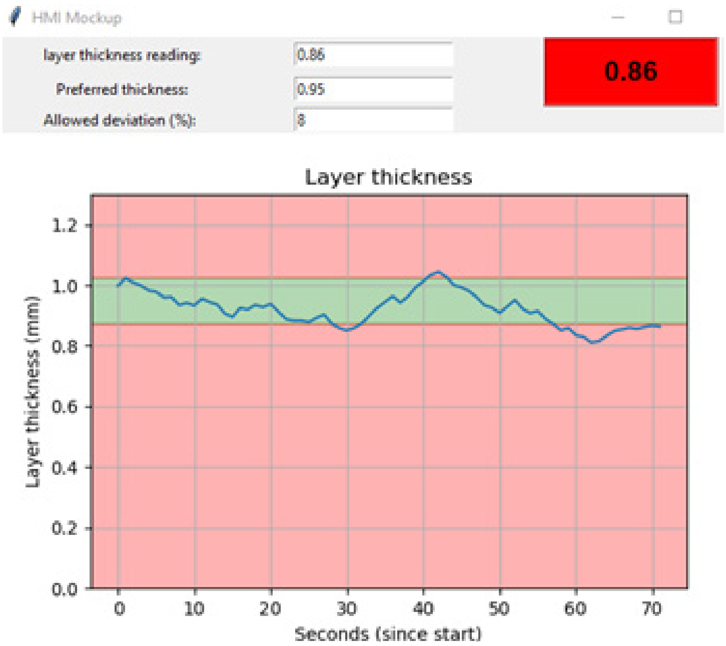


Figure 42 - Mock-up of a layer thickness information tile, made in Python, with control limits

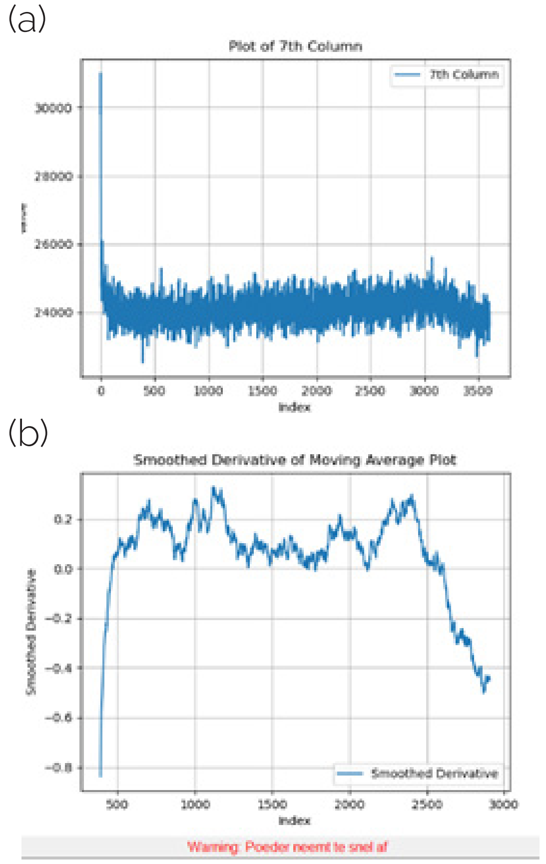


Figure 43 - Top graph: Raw sensor data
Bottom graph: Filtered derivative including waring

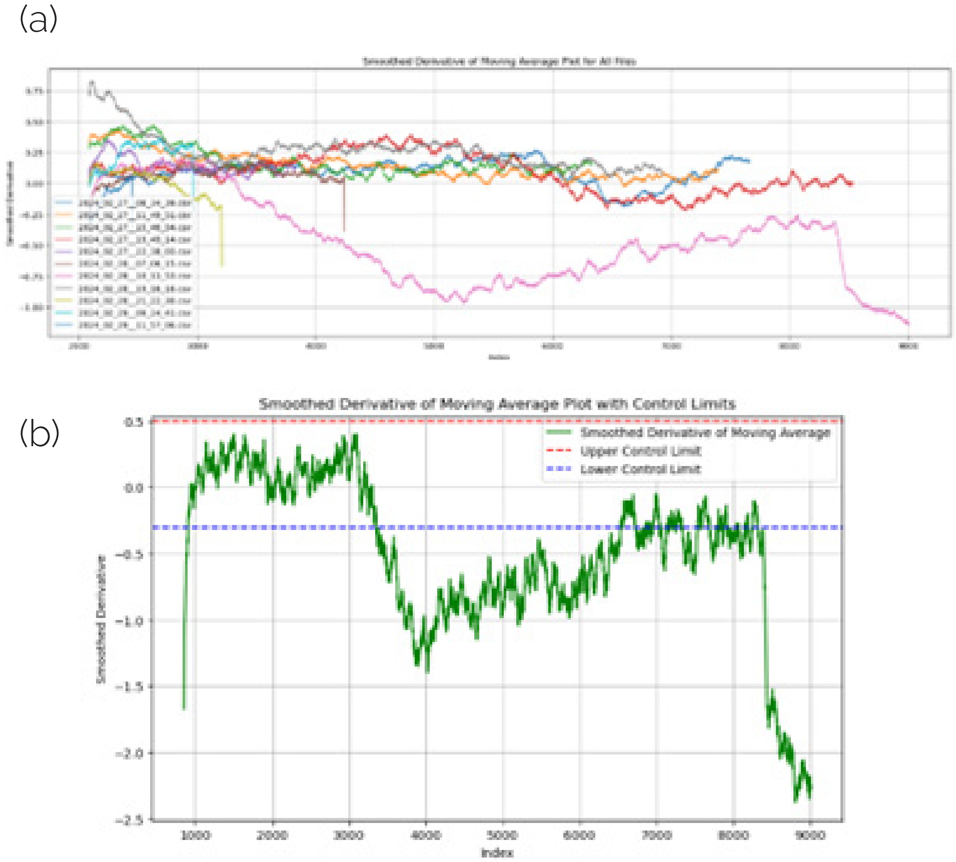


Figure 44 - Top graph: 11 derivatives of cladding sessions (purple line is the session with broken tube)
Bottom: Derivative plotted with control limits

Powder flow alert tests

During cladding, it is essential to have a consistent flow of powder. Leaks in tubing and errors with the hopper or material can all distort the powder flow. This makes the powder flow a helpful indicator in the traffic light system. A red light could indicate the decline of powder flow after a tube delivering the powder wears out or breaks unexpectedly. To keep this from happening, they are connected to a lifetime timer. If a tube has had its lifetime hours, it will be replaced. However, at VHT, there were still incidents where tubes unexpectedly got a small leak. If the data from the powder sensor is examined, the point where the particle count trend started to decrease can be found, even with, in this case, a small leak. This leak was eventually spotted because there was powder on the floor. Not because it was noticed on the Sensor Monitor graph. To detect this decrease, multiple recordings of powder sensor data were plotted, the moving averages were calculated to filter out noise and peaks, and after that, the derivative was taken and graphed. This was plotted for all the measurement data (Figure 44a); in this data, there is a small amount of variation in the trends of powder flow through the tube. However, in the case where a tube started to leak, the slope/derivative is visably getting too low, so this makes it possible to spot this recording as an outlier. This is helpful because now live data can be used to monitor. Take the moving average, differentiate the moving average to get the change in the flow and eventually this can be used for monitoring. This conversion is important because the powder sensor always starts at slightly different values, and multiple sensors with different sensitivities are used. For this live data, an UCL can be set and, more importantly, an LCL to monitor if the decrease gets too much. In a test program (Figure 43b), this was tested, and an error was given when 5 data points were outside of the control range. The decline started at 3200 seconds, and the error was given at 3500 seconds. This five-minute reaction time is reasonable with a small leak. This small leak was not detected using the old interface. This leak was happening for 97 minutes, and only a little powder was spotted on the floor, while 19.4 kilos of powder was supplied during this 97 minutes. Also, the bead seemed normal and unchanged even when the particle count dropped from 24.000 to 20.000, which is a decline of 16.67% over the whole cladding process. The fact that nothing was noticed at this time makes it important to get such indicators. Because a 16% decrease in powder flow may result in a layer thickness that is too low.

ANN tests

As shown in the research, ANNs can be a helpful tool in finding patterns and automating the recognition of specific parameters. The EMAqS camera view is used to get a good overview of the quality of the weld pool. For example, pictures were hung on the machine to show a correct weld pool and a view of what an incorrect weld pool looks like. To find out if ANNs can be used to spot these kinds of differences, a standard convolutional ANN was trained using Python and TensorFlow. The input of the ANN were hand-selected pictures of the process. These pictures were manually classified into three different classes: Bad EMAqS, Good EMAqS, and Turned Off EMAqS. During training the ANN 'learned' what kind of picture belongs in every group. After training, the ANN could classify similar pictures it had never seen before into the three classes.

In the code used, there is an option to calculate the accuracy. For this to work, a more extensive dataset is needed also there are no guidelines for the classification so no entirely correct training dataset can be made. However, these tests prove that the ANN can generally see if the process is running correctly. This ANN could then be used to check all pictures the EMAqS saves in real-time automatically and, in this way, create an alert that will notify the operator if it classifies the process as "bad". This is something the operator is able to do; however, the ANN can check every picture at all times. Only it is impossible for the operator to keep their attention on the EMAqS pictures all the time. Figure 45 shows the images input into the ANN and the resulting messages.

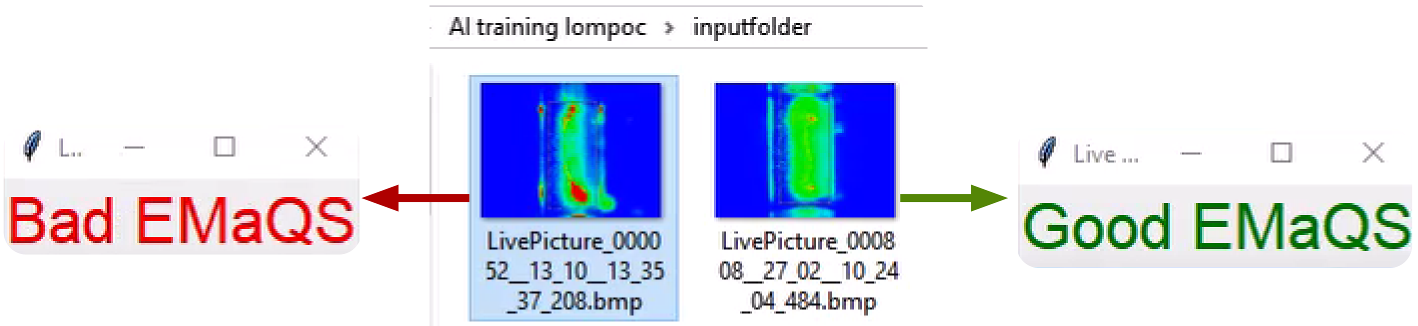


Figure 45 - Python ANN watches a folder and classefies any picture entering the folder.

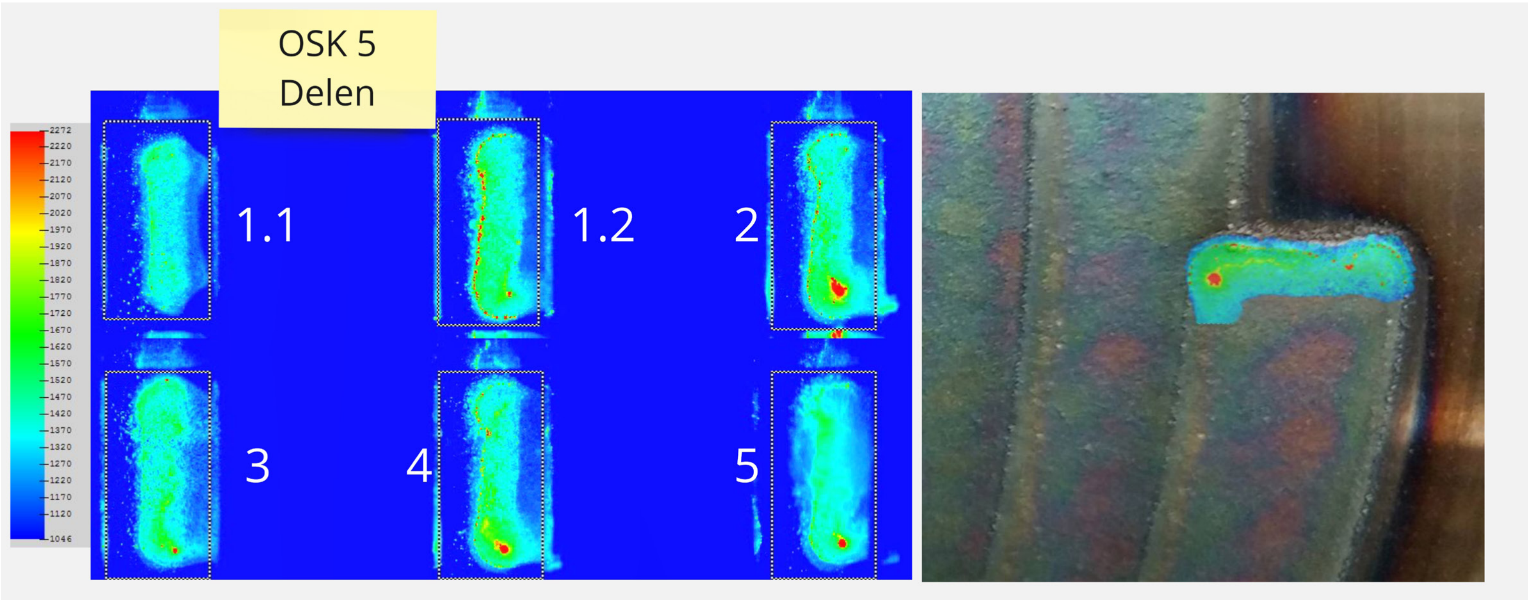


Figure 46 - Five tests with snapshot of how the general EMAqS picture looked durign the test

Even when analysing the EMAqS images by hand, it is hard to say how the resulting bead will look. In Figure 46, five images show the process during five different test sections on a rod. Over these five sections, multiple parameters changed. Section one is made up of two layers: a colder, thin first layer and a thicker hotter second layer. As can be seen on the right side, the hot spot usually seen at the bottom represents the part of the bead that overlaps over the last pass. Here, it is expected that the slag of the previous layer will boil up and get extra hot under the influence of the laser. Later, when Xiris images were also available, it could be seen that bubbles and floating slag get extra hot and cause the hot spot. Bubbles of slag could possibly become extra hot because the gas insulates them and have a less reflective surface.

Xiris thermal / visual camera installation

The new camera that was installed during this thesis has some additional features that will help give more insight into cladding at VHT. It can output its data in real-time from the software and comes with software to analyse the live video view. It has a low sensitivity to emissivity changes, which is necessary for metal thermography [63]. They also claim it is capable of seeing through weld fumes better than CMOS or NIR thermal cameras. It is also capable of high-speed imaging. After installation, it became apparent that the visual camera gives a clear view of what is happening in the meld pool and lots of new data to analyse. The thermal camera gives a bigger picture of the heat distribution; however, it cannot be compared directly to the EMAqS as the temperatures do not compare.

Some relevant features [63]

- Able to record and stream video
- Output data only when cladding is on
- It can automatically output the edges and the width of the bead
- Measure temperature at any location
- .csv recordings with temperatures, widths, sizes and area's
- The software can open different windows, and the user can select which to use.
- Can detect the position of the hottest point.

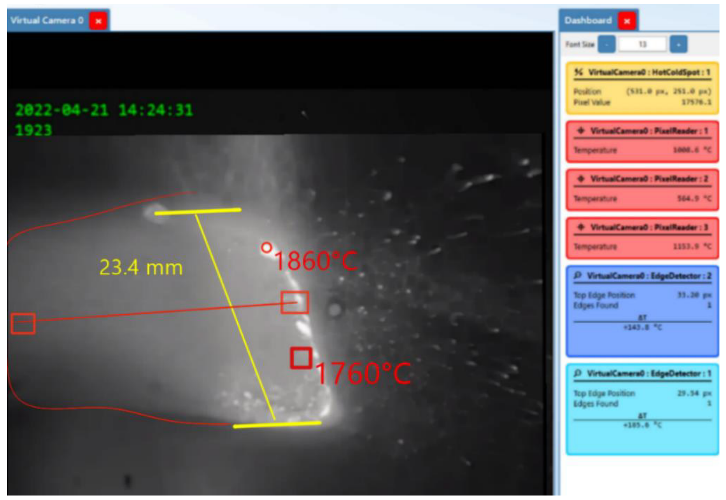


Figure 47 - Xiris software and function overview

Observations after installing

The hot spots observed with the EMAqS camera, or some, look like bubbles and slag on the new Xiris cameras. The surface of these bubbles are isolated from the melt pool by some gas. This makes it so the laser can heat this material more. During production and general testing, the new cameras were watched intensively. During production, many parameters are adjusted based on the general size and shape of the melt pool. Suppose there are specific values describing the desirable shape. In that case, this shape can be logged in the database, and found out how this influences the process and how far this may vary before it causes problems during quality control.

One of the first apparent indications of the quality of the weld pool was the straightness of the front of the weld pool and how uniform the shape is. On the left the front of the weld pool is straight and there is no dip in the middle, on the right there is a dip. However, in the thermal images and in the images, the laser already lights the substrate in the spots where the melt pool is not yet located (the dip). This could cause the substrate to heat up more than desired. This could influence the CIMS reading by melting the substrate's profile. It can also indicates that the weld pool is too cold, and not all the material is melting. In extreme cases, the dip will increase so much that holes in the coating will occur. Not the tiny holes visible after honing caused by pores but complete holes in the coating. The new Xiris software has multiple options for selecting a 'blob', which can be done by temperature or intensity. This blob can then be analysed according to its shape. The analytical tools for this shape has to be analysed further.

(a) (b)

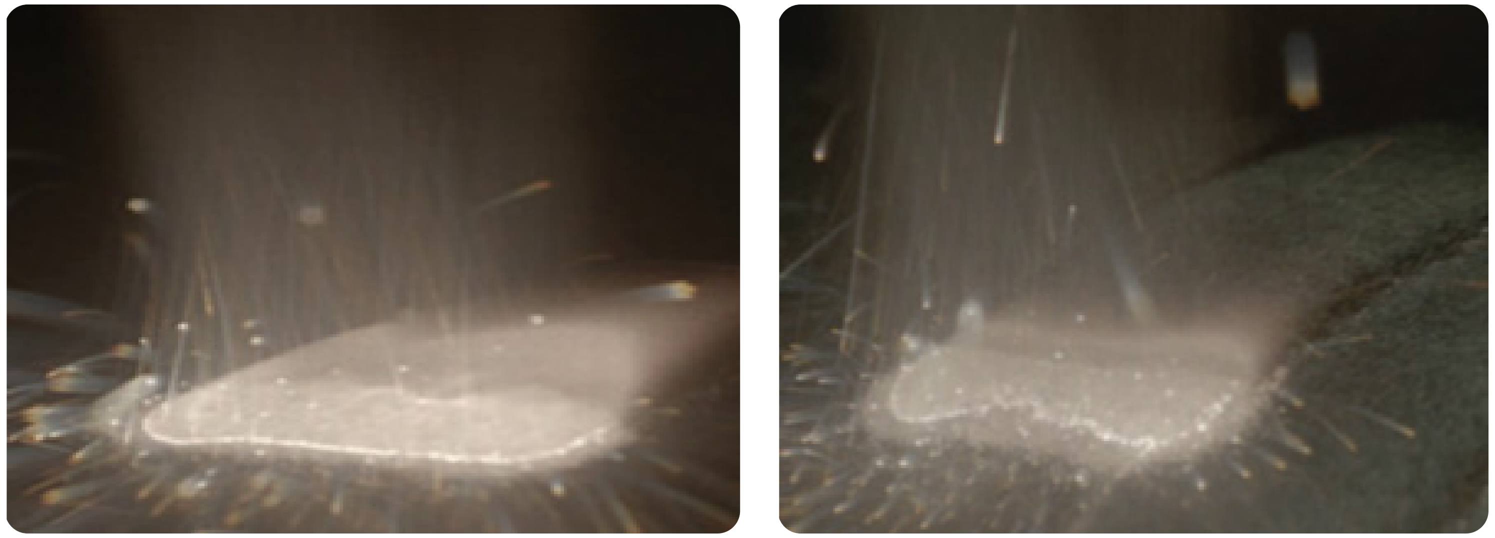


Figure 49 - Xiris images of the weltpool at VHT, (a): correct straight front, (b): front with dip, lower quality pool

The solution to the dip in Figure 49 was counter-intuitive. To solve this dip, the power was decreased, and the nozzle distance was decreased. It may look like the melt pool should increase in temperature to ensure the whole area would meld. However, the powder focus was more important in this case. Changing the distance focused the powder better, and the 'straightness' of the front increased. What changed in this focus is unknown, as there is no way of knowing exactly where the powder ends up. The nozzle has a designed working distance; however, how wear and carrier gas flow influence this is unknown. This is why the installation of the coaxial camera, including a laser to illuminate the focus spot, could be interesting. Also, the LISEC from Fraunhofer can give this insight; however, this proved to be an expensive device. When this powder focus can be logged, VHT also needs to know the laser focus. For this, the laser could be pulsed on a test plate. This leaves a mark on this plate that can be looked at through the coaxial camera. The focus of the powder can then be adjusted to match the exact laser focus. Simultaneously, a new nozzle will be installed for this coaxial camera. This nozzle can be moved in X, Y, and Z directions to move the powder focus. So, with these adjustments, the powder can be set correctly in relation to the laser. When this is set correctly, the position of the laser in relation to the work-piece/fixed base is essential. From design, this is done by end stops for the movable arm, but to be sure, a place can be made where the laser can pulse on a set place to calibrate this position.

In some situations, powder focus is not the solution; when the weld pool is too cold, holes will also form in the layer. Figure 48a provides an excellent example of a weld pool that is too cold, and the coating is not attaching correctly. This causes blobs of material on the substrate to not bond. To the right (Figure 48b), the correct power setting was used.

(a) (b)

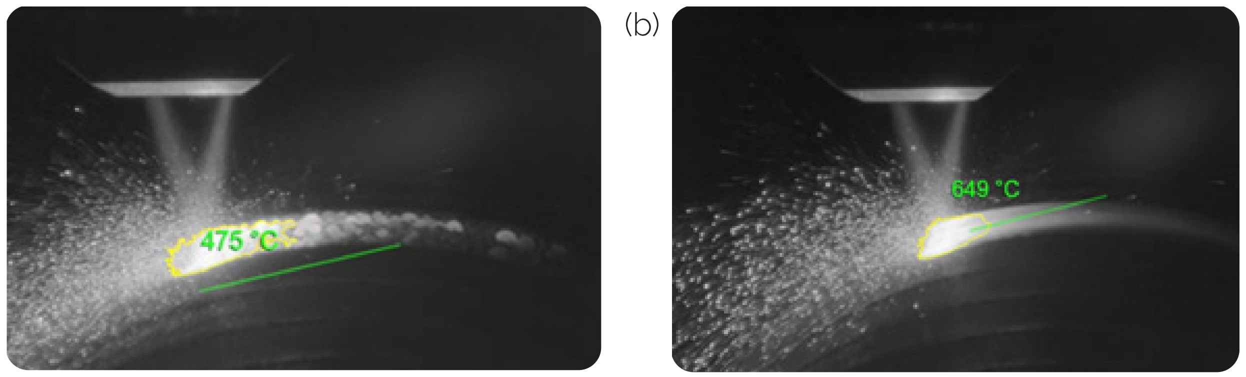


Figure 48 - (a): melt pool not hot enough (b)correct temperature (green values are false)

Discovered pit

Some pits/holes were found when examining a rod. To find the cause of these holes, the distance from the starting position of the bead was measured until the hole. VHT did know the starting position, the time it started, and the speed at which the x-axis moved. This makes it possible to estimate the elapsed time until the hole was formed. This made it possible to play the Xiris footage of when the hole was formed. After watching a few minutes of video, the cause of one of the holes was found. A particle coming from the nozzle absorbed way more energy from the laser than the powder, causing a hot spot in the image. This particle looks to be an impurity in the powder; the particle size of this impurity may also be bigger than the average powder size. The guess is that it has been a particle of wood, plastic, or slag after examining the sieve mesh size and the particles that were regularly caught in it. It is a logical conclusion that it can be a particle smaller than the filtered particles that were causing this hole. Plastic, wood, and particles from unknown materials are mostly found in this sieve. This points in the direction that occasional holes during a good process can be the result of impurities in the powder. Figure 50 shows the detection of the particle that caused the hole. In the video, it is visible that a particle coming from the nozzle gets heated until the software recognizes it as the hottest point in the image. It ends up in the melt pool, where it keeps ejecting gasses and, in this way, forming a hole that can be seen a pass later.

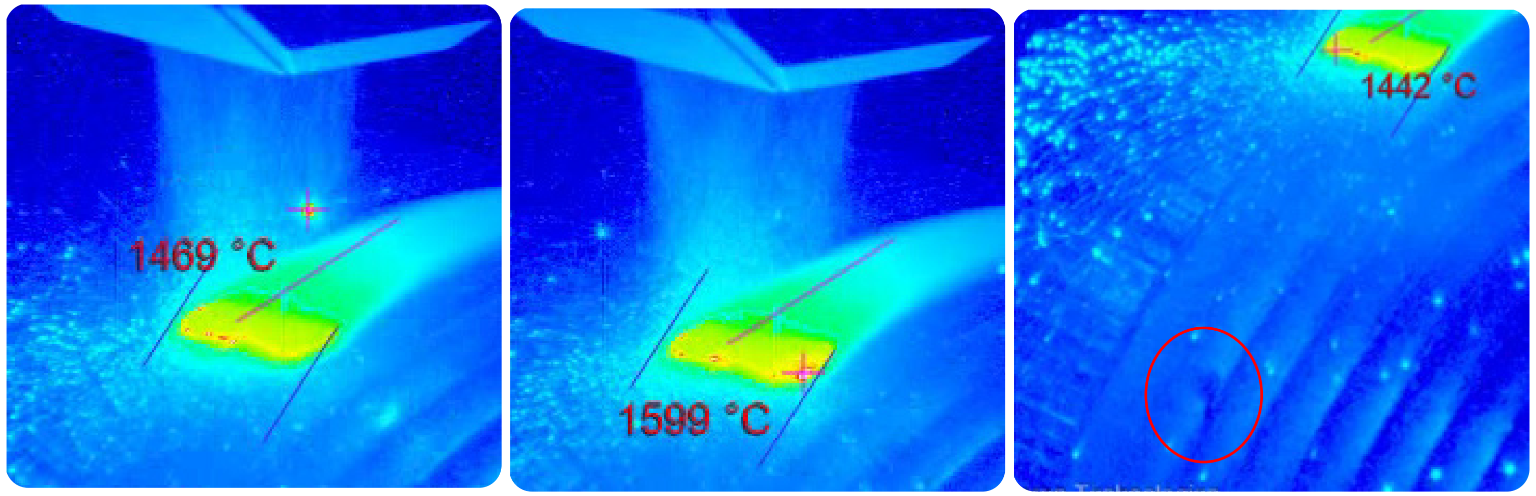


Figure 50 - Detection of a hot particle (impurity) by the Xiris camera

Future prevention

The following steps can be taken to ensure this problem is detected sooner or does not happen at all:

- Check the quality of the powder and, if necessary, talk to the manufacturer.
- Sieve the powder with finer mesh.
- Leveraging the existing hot-spot location data, log the moments and positions when the hottest spot intersects with the powder stream and the frequency. This will enable VHT to identify when and how much this happens.

The melt pool must be in the same position every time for this to work. This can be done by creating permanent guidelines overlays in the video to check if the camera has moved in relation to the weld pool and readjust them if necessary. It could also be possible to make a rigid mounting bracket that cannot move as the current mounting solution is not fixed and can move. When this position data is correct an overview like in Figure 51 can be plotted. The two frames that captured the impurity in the powder stream are shown in the red square.

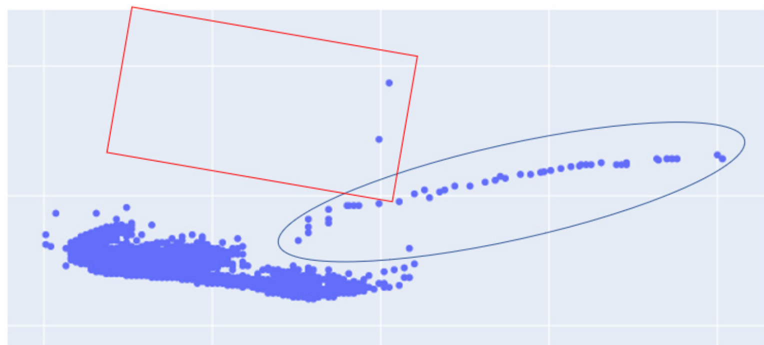


Figure 51 - Plotted positions of the hottest point in the image for every frame

Exploring possibilities

In Figure 52, the hot spots over five recordings are plotted. The hot spots in the blue circles and some on the left are created when the laser is turned off, and the moving weld pool is the hottest spot in the picture. This was checked by looking at the timestamp of the data points and the recording. The hot spots at the left are sparks at the beginning or the end of the recording. This means that a square can be drawn (e.g. the red one, Figure 52), and monitored for the case that there are points within this square during normal operations, excluding the start and stop moments. Then this can be logged and looked up in the video files. This will allow VHT to see in real-time when these events occur and thus Figure out how many holes are created in this way. Also, when this data is exported to the database, it can easily be plotted automatically for each selected rod.

This occurrence could be seen in two frames, so 2/60th of a second. An operator cannot spot this while watching the machine for hours at a time.

This is why a code was created that can read live data or .csv data and then output this:

"Number of rows: 2
Timestamps of filtered rows:
['2024-05-22 12:43:36.756', '2024-05-22 12:43:36.775']"

These are the two timestamps of the frames in Figures 50 and 52.

In Figure 53, much bigger areas are covered with hot spots, making it harder to spot abnormalities. This happened because one cladding session had a too-cold melt pool, so the spatters were more often the hottest points. This happens rarely, so when the individual cladding sessions are analysed, this will not cause problems.

The frames in Figure 54 were found using the new method, and a particle was found to be hotter than the melt pool. This did not result in a noticeable hole in the substrate, but it proves that this method can spot abnormalities in thousands of frames.

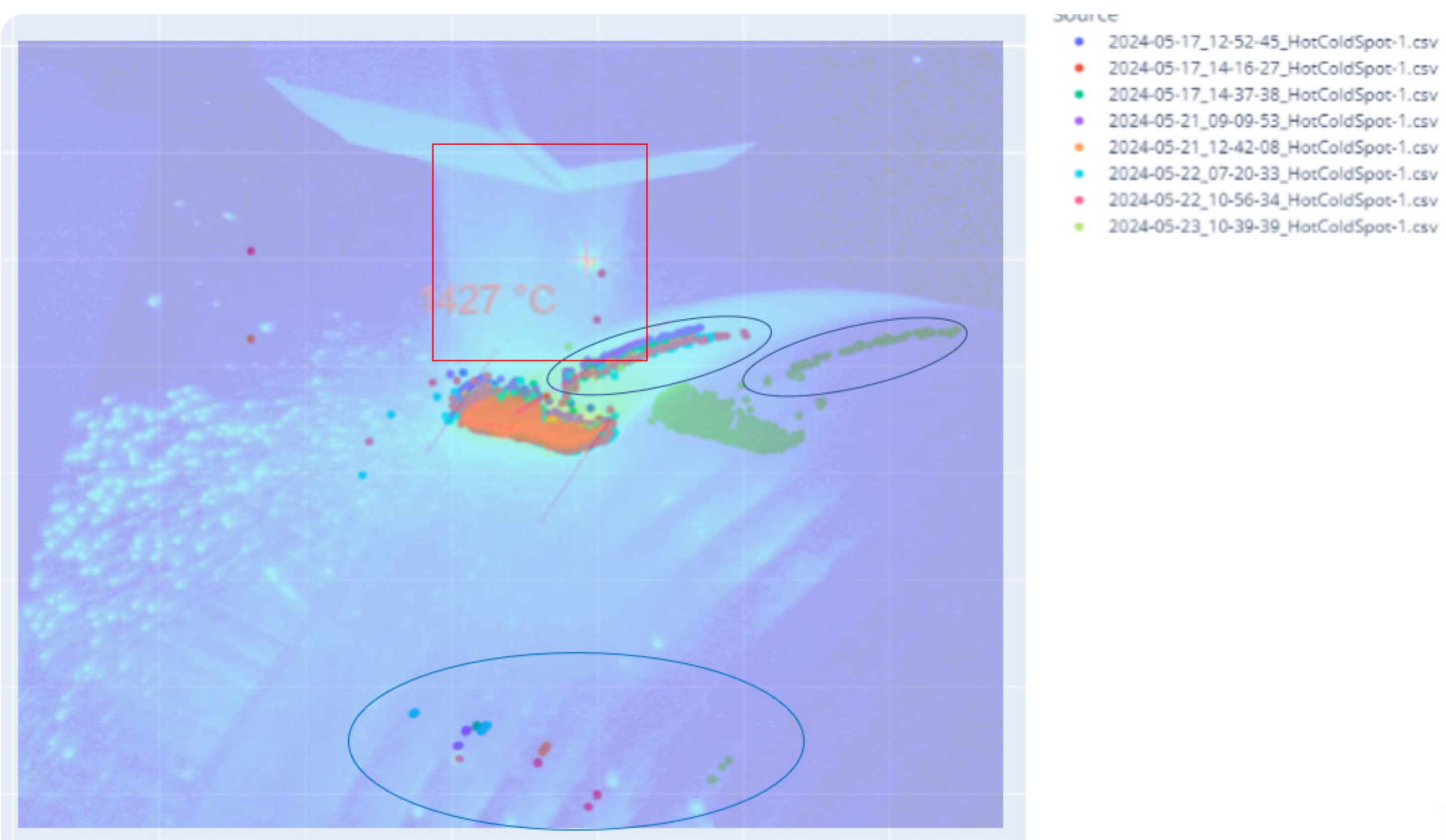


Figure 52 - Plotted positions of hot spots over the actual location in the image, multiple recordings and days

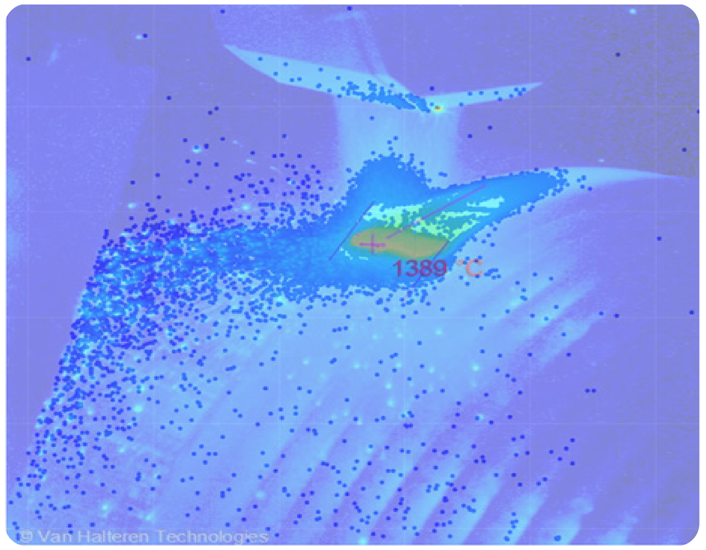


Figure 53 - 17 different clad sessions all hot spots from all frames, some recordings have dots all over the place

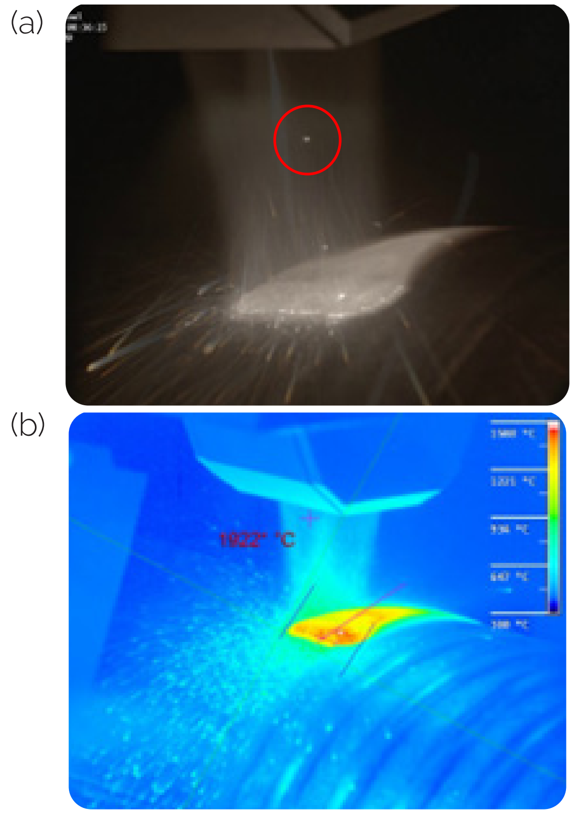


Figure 54 - Other hot spots found in the powder focus by using the new detection method (a): visual (b): Thermal

Temperature decrease

Cracks were found in the coating during production. This can happen when the temperature is too low, and the coating cools too fast, which is why the comparison in Figure 55 is made. The right green line (Figure 55b) is the mean temperature of the Xiris hottest spot measurement. The end of the clad from the time 07:36 had cracks. So, the decline of the temperature could cause the cracks; however, after further analysis of the images. The decline in this picture is probably the result of the thermal camera getting too hot. The complete video area reduced in temperature during this session, including parts that should have constant temperatures. The temperature sensor inside the camera indicated it indeed got too hot. From this session forward, the camera was connected to the water cooling channels of the cladding machine so it did not increase to 60/70 degrees. This way, the false decline, as seen in this video, does not happen again.

The declining temperature is not visible in the EMAqS data (left blue line), proving it was solely the result of the camera overheating.

The SIMS ridges in the rod cause the fluctuations seen in the graphs. These peaks and valleys in the substrate's height make the melt pool periodically hotter and colder. This is known because the frequency of passing peaks and valleys is the period of the fluctuations. Another frequency can be found when a rod does not have a CIMS profile and is clamped off-centre, making it oscilate. When comparing data in the dashboard, it would be helpful to display this oscillation.

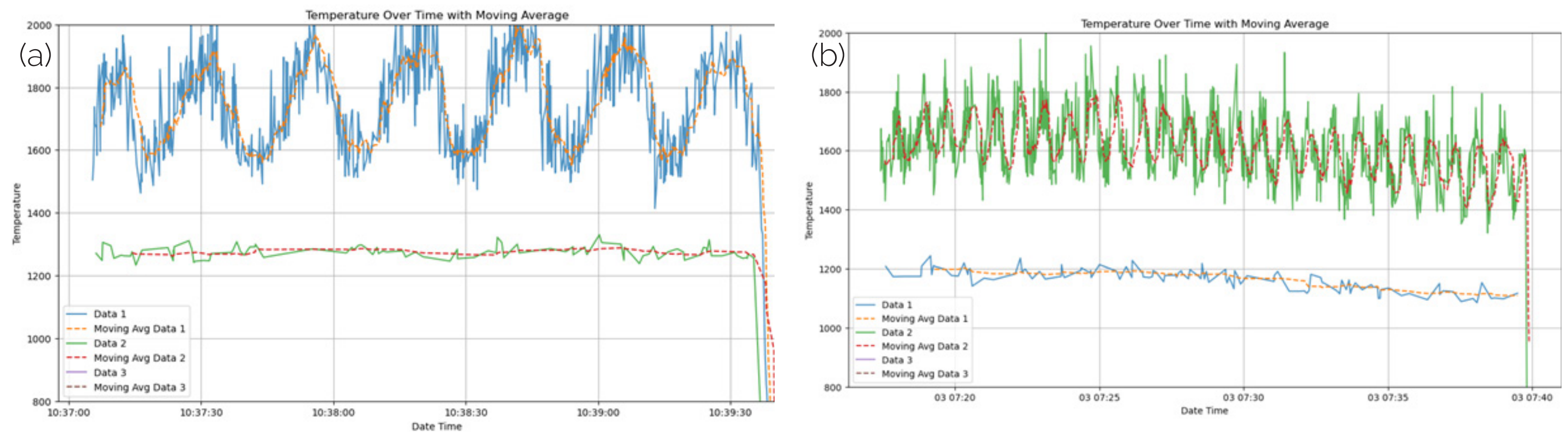


Figure 55 - Graphs of cladding temperatures with Python

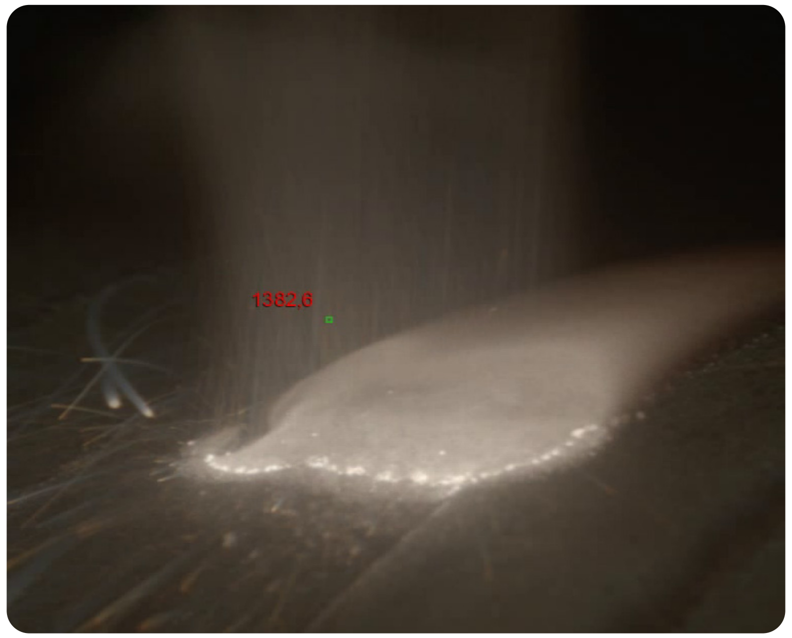


Figure 57 - Holes in coating because of contaminated rod

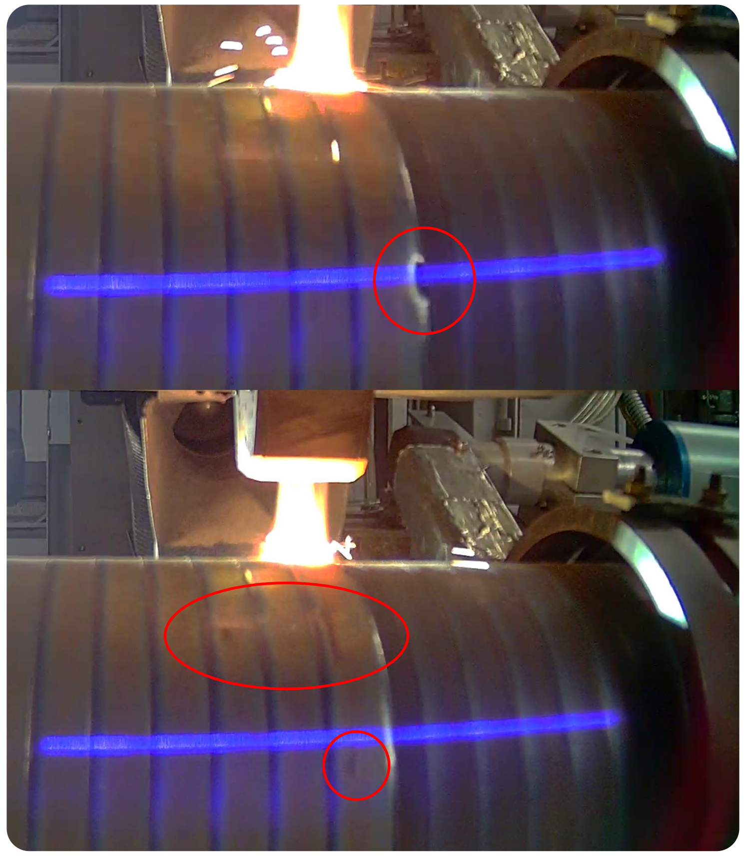


Figure 58 - Holes after additional passes

Contaminated spots on the rod

During research, it was found that grease on the substrate could cause holes [8]. Van Halteren has done multiple tests with different kinds of contaminants. White chalk, different coloured markers and grease; however, as this is not beneficial for the quality of the coating, it did not cause imidate holes. In a more recent case where the Xiris cameras were already installed, contaminants did cause problems. In Figure 57, a snapshot is shown of a hole forming at the side of the weld pool. This hole was located at the side of the weld pool and filled with material the next overlapping pass. This happened three times, as seen in Figure 58, where only three marks are left. After honing these marks, resulted in three cracks. The footage of the first layer was examined, but nothing weird was found. Only later, when looking at the bare rod in the video, was the same pattern of three marks seen at the same position. This meant that these marks had something to do with the cracks. The particular rod had been lying around for a long time, creating some places of rust. Three such places are expected to be the cause of the cracks. Finding this cause took much time as it was hard to lookup the exact moments. This is why, later, the PCs and process cameras were synchronised. In combination with the database, this makes it possible to insert a position on the rod and look up the time the nozzle was near it. This time can be found in the Xiris videos, which now have an overlay of the exact time. This process is explained in Figure 56.

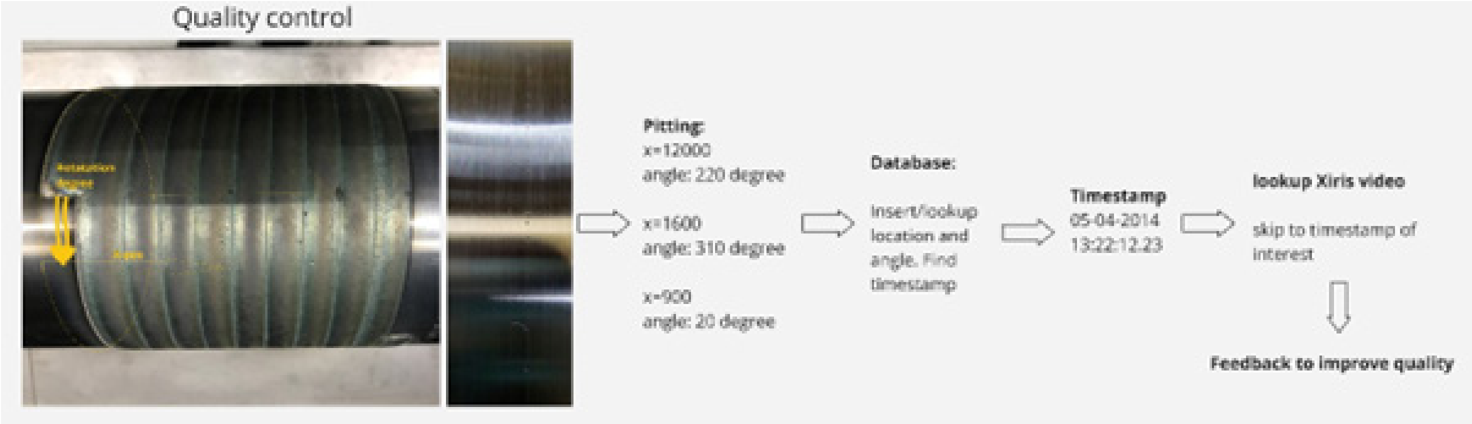


Figure 56 - Method to find data/videos corresponding the found defects

Powder sensor range and accuracy test

The disc speed was increased by 10% in steps to test the linearity and accuracy. The results were better than expected but were not entirely linear. This can be seen in Figure 59 (b). Here, there is a relation, but it is not linear, and the results have some errors. However, it does not show the same decline or increase sometimes observed during production after stabilising. But it can be said that a decrease of -+10% must be measurable. Some expect the sensor to get hotter during production, which could cause weird trends that are sometimes seen in the production data of the powder sensors.

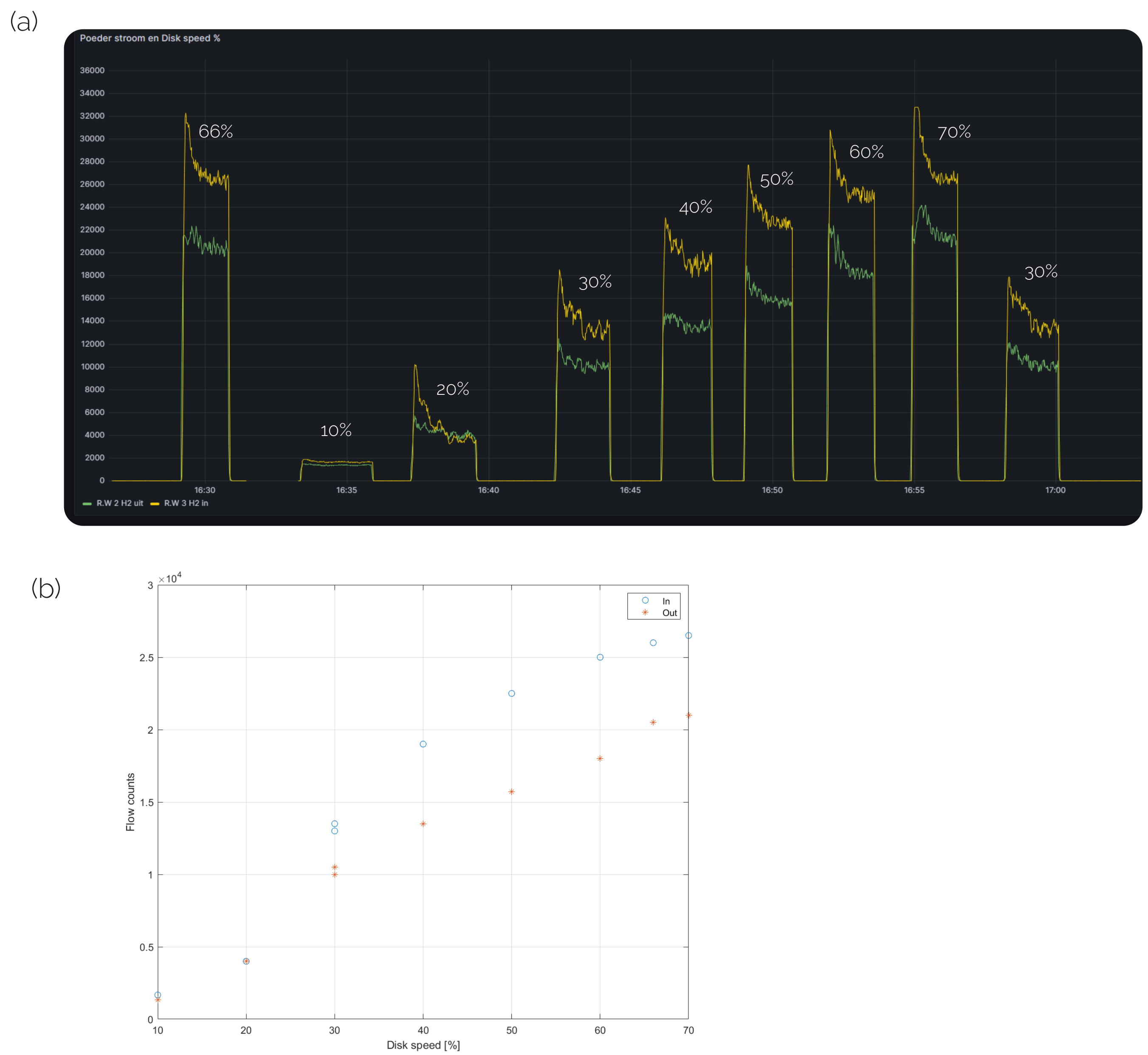


Figure 59 - (a) Output of powder flow for different hopper speeds in % of maximum, (b) plotted averages of the count value against the disk speed (%)

Pressure drop caused by leak

The hopper supplies a set amount of gas (L/min) to carry the powder trough the tubes. This builds pressure, which is now logged in the database. This pressure is about 1.10 bar, depending on the amount of powder supplied. At some point, the machine would not reach this level anymore (950 mbar). After some troubleshooting, a hole was found in the tube near the hopper, causing the pressure to decrease. When this tube was replaced, the pressure did reach 1.1 bar again. This occurrence has made it interesting to keep an eye on this pressure. Adding a warning for a too-low pressure can help detect such a leak in the future. This warning could turn the powder indicator orange or red, indicating a problem. A leak that is positioned further away from the hopper may be harder to spot because of pressur drop in the tube.

(a) (b)

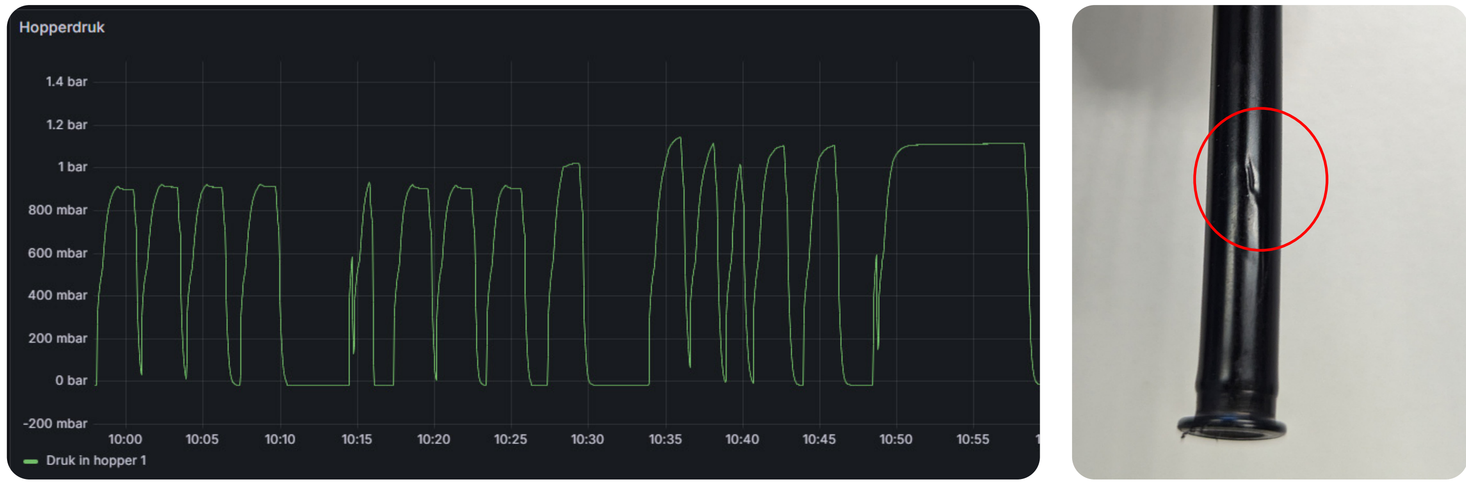


Figure 60 - (a): Hopper pressure graph taken from dashboard, (b): The leak causing the lower pressure

What information to monitor?

Before an interface can be made, it is essential to know which information is most helpful to the operator and to analyse the data afterwards. Some of these critical parameters (see 'the most important process parameters') are values that should be constant and input into the machine: speed, pitch, laser spot size, laser power, offsets, hopper speeds and gas flows. These parameters are regulated to be as constant as possible and can be seen as input variables. Apart from this data, some sensors measure the output variables like the exact gas flows, pressures, speeds and temperatures. This is the more interesting information because they measure what is actually happening. The differences between the actual values and the setpoints are essential to ensure that the process is within specifications. All the sensor data and visual camera information can be monitored. So, the complete set of process data includes all the input parameters relating to the process and all the output data that can be gathered.

To create a uniform, correct meld pool, the heat input (kJ/mm) must match the powder flow and substrate temperature. When this is correct, the powder will melt in the required area, creating the layer. So the temperature of the substrate and the temperatures and distribution of heat in the weld pool are essential to have right. This is why the temperatures derived from the thermal cameras and pyrometer, including a visualisation of the temperature and distribution (thermal images), are essential data to monitor. This is why the EMAqS images were used extensively and now the visual Xiris images.

The laser power is as good as constant and does have a power input meter; however, this data cannot be accessed yet.

Apart from making sure the powder uniformly melts in the weld pool, it is essential to know the dimensions of the resulting cladding layer, which are measured by the layer thickness sensor. Also, the Xiris camera can analyse the bead geometry and output the width of the bead and even the area and shape. This data helps estimate the resulting layer.

Dilution and heat-affected zones are essential parameters that can influence quality as specific hardnesses and iron contents should be reached according to the customer. The heat-affected zone and the temperature gradients in it have an influence on the hardness[12], and the dilution influences the iron content, and so influences the rust resistance. These phenomena are not directly measured and can be derived/estimated from pre-heat temperature, melt pool size and temperatures. In [19], a computational model was used to predict the dilution rate from those parameters, and they found there is. However, the most significant relation found was melt pool width. This width had a significant influence on the dilution. This will, however, naturally be affected by the laser and powder spot size. So it would be helpful to log this, but for real-time monitoring, it will need more research, sensors, calculators or AI analysis to make predictions for this on live sensor data.

The supply of powder is a complex process, and things can go wrong, like a leaking tube. If used correctly, sensors are beneficial for quickly detecting this. A leak can be the cause of a bead that is reducing in size. The powder sensors and clad width are therefore important.

Safety,
Some aspects of the process can be dangerous, also parts can break. To make sure the operator and machine are kept safe some sensors are placed that can indicate if something may get too hot or damaged. These are values like nozzle temp., protection glass temp. and the dust monitor. They need to be included for safe production so should be included in the dashboard.

In conclusion, most measurable parameters are already available somewhere, and what is more critical is collecting and correctly displaying them. This is also what was missing in the old display. Having the data together and comparable for any time window is essential. In this chapter, there was looked at some individual sensors and how the Xiris camera brings more insight into the process. The methods used during the exploration phase can be included in the eventual dashboard. More sensors could also be added, most promising the ultrasound microphone for real-time crack detection and reading the exact speeds of the different axes.

09

Logic and relations

The data collection infrastructure works; the complete set of process data is collected with the correct timestamps. By exploring this data, meeting with the process engineer, and talking to the operators, there is a sense of what they want to monitor and analyse. In addition, the kind of logic that will be included in the dashboards is described, making building the actual dashboards the final step. In this chapter, the build dashboard and the workings are described.

Logic and process health

The logic behind the 'traffic light' interface will define how the operator judges the state of the process. This makes it essential that the information that is communicated is correct. The idea is that a few notable indicators communicate if their own sub-part of the process is within specifications. For example, one tile could be coupled to all powder flow information. The data from the powder flow sensors can be converted to a metric that shows the average rate of change of this 'count' in a certain period of this incoming data. From here, simple logic can be used to give a warning and turn the tile red if this value drops too low and the average rate of change is out of the ordinary in comparison to what was tested/determined. This tile will now become red; a red tile will mean that the process needs to be stopped and checked, as a leak in the powder tube or insufficient powder delivery will result in an unusable coating. This describes one example of a value that can be monitored in such a way to output a value that can turn indicators red or green. A slightly wider bead noticed by the Xiris camera can be a problem, but it does not necessarily need to be. In this case, the tile accounting for this category can become orange, indicating to the operator that something may be off and that more attention is required. If this wider bead however takes place while the powder flow decreases and the melt pool temperature increases, it can be said that it is part of a broader problem, and this is a situation in which the process should be stopped and so the tile should turn red. This kind of logic programming can be done for multiple sensor and machine parameters, and so build the whole interface. This logic will include limits, relations, and information about the process. These can be logical conclusions, conclusions from literature, or things that were learned from analysing the quality of the rod after cladding. In a way, this logic will determine if the process is within the quality limits.

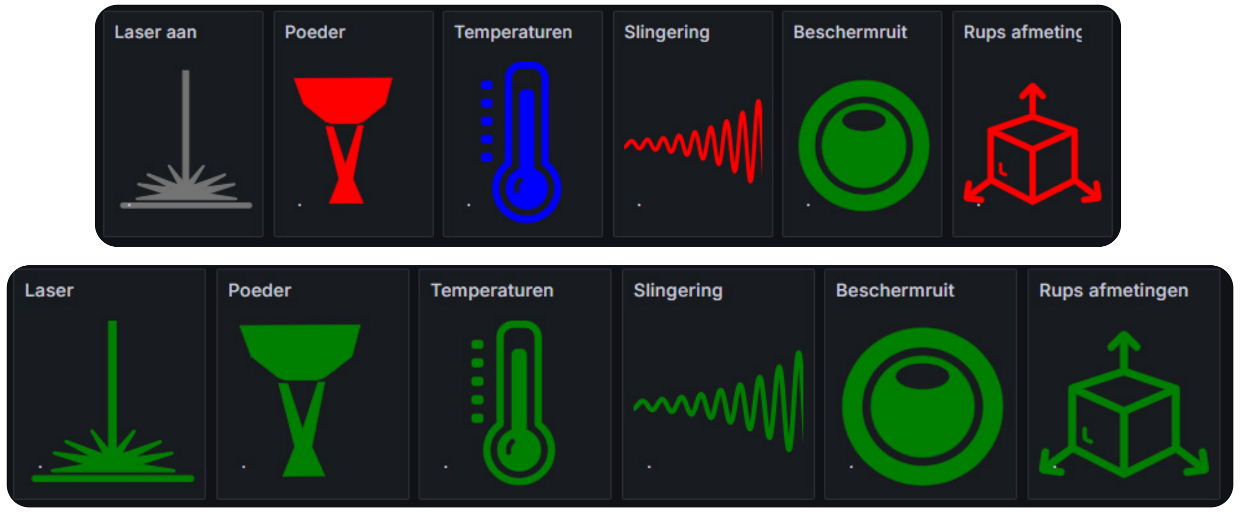


Figure 61 - Process 'traffic light' indicators; top shows indicators when there is no cladding happening and parameters are not within spec. Bottom shows a good process.

What is collected?

Source	interval	device	Data examples
Lompoc	5ms (many points)	Fraunhofer pc - Emaqs	Melt pool temperature, scanning speed, set laser power
Sensor monitor	1s	HMI	4 powder sensors, nozzle temp, optical protection glass
LineScanner	Custom (20ms max)	Fraunhofer pc - scanner	Distance to the rod, layer thickness
S7300 PLC	Custom (max unkn.)	PLC Machine net	X-pos, laser-on, induction-on, production order, Serial Nr, system variables
Xiris thermal	Custom (17ms max)	Xiris pc	Custom temperature measurements, clad area, clad width, positions
Xiris visual	Custom (25ms max)	Xiris pc	Visual overview cladding process

Current logic used

In Figure 61, six different indicators are shown. The color is depended on the data it receives.The current calculations are as follows:

Laser

It picks the last five minutes of data, looks at the last tag, and checks if "laser on"=true. If the laser is indeed on, it will change from grey (off) to green (on).

Powder

It takes the selected hopper as input and requests this data for the displayed timeframe. Then, it converts the data to a moving average of 1000 seconds, and the derivative of this per second is made. This derivative is arrogated every 20 seconds. When doing this, it will give a value every 20 seconds on how much the trend declined or inclined. This value was calibrated to give a warning if it became lower than 0.8. This indicated the leaking tube in 6 minutes using that data.

Temperature

As the EMAqS is one of the more reliable temperature measurements, this value is used for this indicator. It should be above 1400 °C and below 2000 °C; otherwise, it will turn red.

Swaying

The distance to the rod is taken from the Modbus data. This indicator looks at the last minute, taking the lowest and highest value and subtracting the lowest from the highest. If this value is above 2mm, the indicator will become red.

Protection glass

This indicator looks at the last value for the protection glass and will turn red and yellow when it increases above 50 °C because this is not recommended. However, as this almost always happens with this particular setup, it will only turn red when above 65 °C.

Clad dimensions

This indicator looks at the last clad with a value and checks if this is within 40 to 80 pixels; otherwise, it will become red. This value changes a lot from time to time, so it might be a better idea to look at the change just like the powder flow.

10 Iteration and testing

Because it is essential to see how the interfaces are used, a first version was created and sent around to anyone involved in the laser cladding process. The dashboards themselves have places to put feedback. However, most feedback was communicated verbally and logged in the feedback log on the next page. During the iteration, the bugs and illogical features of the interfaces were slowly ironed out.

In Figure 62 the feedback form added to some dashboards is shown. It is meant for the users to communicate bugs and tips for imporvement. During the iteration phase most feedback was given verbally during discussions or when something stopped working. On the next page a list of improvements made since the introduction of the logbook is found. It mostly consist of comments different engineers made about the dashboard. All were solved and taken into account for the new dashboard. In this way, the dashboard was continuously improved during the last few weeks of this thesis and will be in the future.

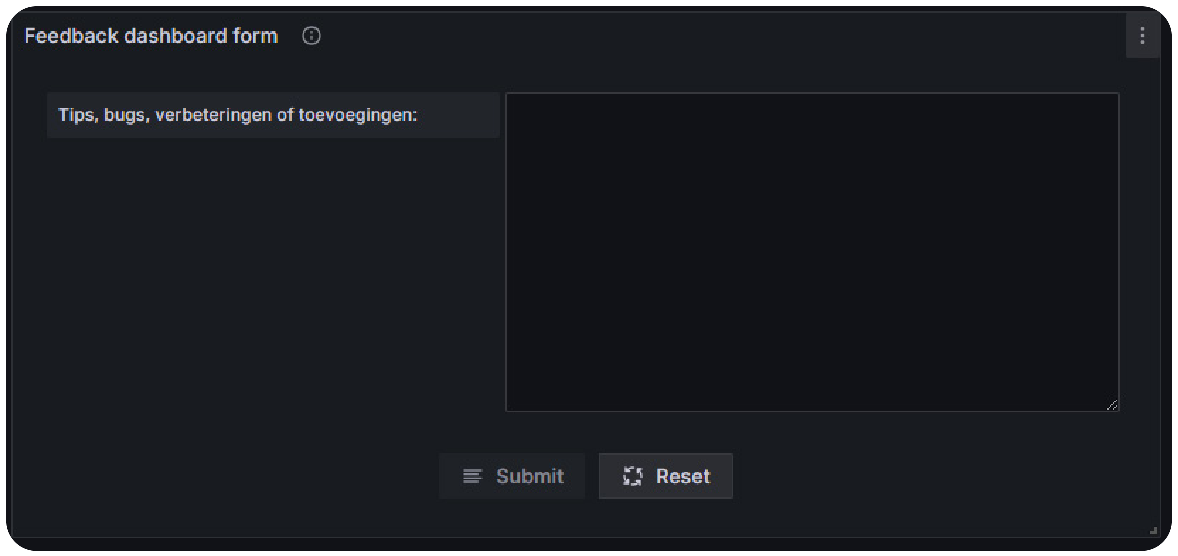


Figure 62 - Feedback form for users to communicate bugs and feedback

Feedback log

Changes since 24-07-2024, when first version was shared

- **Software engineer:** "I cannot see the time the selected rods are cladded in the comparison dashboard" Solution: Added a time hover pointer to graphs
- **Process engineer:** Wanted to know the deflection of the rod at multiple points to fill in documentation for customers. Solution: Added a function in the analytical dashboard where the deflection for the selected time is shown, this can be used to quickly select data the user wants.
- **Noticed:** powder flow does not update when another hopper is selected. Solution: Changed the way the panel collects data, it now works
- Order numbers are ordered in numerical order ascending, so the lowest is on top of the list. However, the newest numbers are the highest so this should be on top. Solution: changed order
- **Process engineer:** Some unrelated metrics are combined in panels, this could cause confusion. Reaction; This was done for efficient space usage, this can be split as the display next to the machine is bigger. The solution was to make other pairs and remove some confusing pairs.
- **Discussion with software engineer:** EMAqS data stream creates 4.5 million data points per metric per week (200 points/s) and Xiris ~1 million per week (50 points/s). This is a lot of data and makes loading slower. Solution: Can be solved by arregration when output in Fraunhofer software is added. This process is ongoing.
- **Process engineer:** could not view distance sensor because too many datapoints were loaded. Solution: Increased allowed size and deleted data points where the machine was off. This stresses the importance to run the redundant data every month.
- **Engineer:** Maybe put disk speed and powder flow in the same panel as they relate to each other. Reaction: splitted some more unrelated after feedback and grouped the disk and powder flow.
- **Engineer:** "We cladded with two different laser powers on the same ordernummer and serial number, now we can only see the last set power, can you add the set power to the power graphs" Solution: Added laser power to the temperature graphs.
- **Noticed:** The logbook/quality feedback stopped working because operators were adding " " spaces in the serial number input, This does not work with line input via the "bussiness form" panel. Solution: Wrote code to replace any space with a "_". To display Logbook and quality info on the dashboards additional grafana variables needed to be made to transform the SerialNr with "_" symbols back to get the right query information.
- **Noticed:** A known bug after the delivery of the first version was the delay of the Lompoc and Sensormonitor data. After some contact with Fraunhofer, it became clear that no direct data output was possible but that the files should be updated in real time. This was not visible in the sent data. However, a tip was given about Windows locking the file or not writing the cache. When the file was manually polled, everything was updated in real time, and data was coming in without delay. Polling the file with two programs at the same time would be unnecessarily heavy on the CPU. This is why a program was made that asks for the file size of the two newest files in their size. When doing this, Windows unlocks or refreshes the files, and Telegraf gets the data in real-time.

11

New dashboards

The data collection infrastructure works; the complete set of process data is collected with the correct timestamps. By exploring this data, meeting with the process engineer, and talking to the operators, there is a sense of what they want to monitor and analyse. In addition, the kind of logic that will be included in the dashboards is described, Making building the actual dashboards the final step. In this chapter, the build dashboard and its workings are described.

Setting up

There are different reasons for users to access the data collected by the laser cladding process. The two main reasons are to monitor the process to act when problems occur and to analyse later how the process went, hopefully learn from the data, and improve future layers. Because of this, two main dashboards are specifically designed for these applications. A dashboard that shows the live data and can warn the operator in case of problems, as well as a dashboard that can be used to search for previous data and analyse this. This can lead to insights into changing the cladding settings or the "traffic light" system on the real-time monitor. Furthermore, more specific dashboards were later added. For example, one to fill in the new digital logbook and fill out the quality feedback form. This data can then be shown together with the analytical data. Also, there is an ability to download data and export graphs. This can be used to supply data together with other documentation to customers who want to check if everything went according to specification. Some customers have asked to see or be able to look into data gathered during production (camera recordings).

Trial and error

Configuring the settings for Telegraf in a way that it was sending data without gaps and sending data quickly and reliably took some trial and error. The batch sizes in which the data was sent and the complexity of the code had some interactions with sending the data. Increasing the one setting made the system more reliable but very slow and increasing the other made it fast but created gaps in the data. This was mostly a problem on an older and less quick computer. As it turns out, making it work once was doable, but making all of it work at the same time and reliably needed some fine-tuning. Also, there is contact with Fraunhofer to make sending some parts of the data more reliable and faster by sending the data from the Sensor monitor, and EMAqS software live instead of parsing the log files.

When creating the dashboard's layout, it is important to keep in mind what screen it will be shown on and what its size will be. Luckily, changing the layout, sizes, and positions in Grafana is fast and easy, so this can be adjusted when the dashboard is finished and needs to be shown. For now, the dashboard is shown on the top right screen of the described interface. To make it fit all panels and make it readable, the sizes of the panels were adjusted explicitly to this screen and saved as a new version of the dashboard.

Functions of the dashboards

Live dashboard

To improve monitoring, the live dashboard was developed. This dashboard will be used to monitor the machine in real-time. The operator does this in front of the machine; however, the dashboard can be loaded from anywhere, making it also possible to monitor it remotely. This could be done by using the new Xiris live camera stream together with the dashboard to get a complete view of what is happening. This live dashboard has the built-in "traffic light" warning symbols. These symbols alert the operator if certain stats are outside of their limits, as described in Chapter 9. The data which the dashboard shows can be selected by time and by the last x amount of time, e.g. 15 minutes or 2 hours.

Analytical dashboard

The analytical dashboard is meant to look up information after the cladding has finished. It selects the data not on the time the cladding happened but on its production order number and the section's serial number. The user can select these numbers, and the specific data will be shown after clicking zoom to data. This overview of data can also show information filled in about the quality and logbook data. This can be expanded with any data preferred.

Comparison Dashboard

It can be helpful to compare different cladding sessions to see what works and what does not, e.g. comparing a section cladded with 12kW and a section with 14kW. This is why a dashboard was made where the user can select two specific cladding sessions by their order number and serial number and compare, for example, the temperatures. This comparison can be elaborated by adding data like the measured hardness of the HAZ, measured layer thickness, CIMS signal, or powder flow.

Logbook

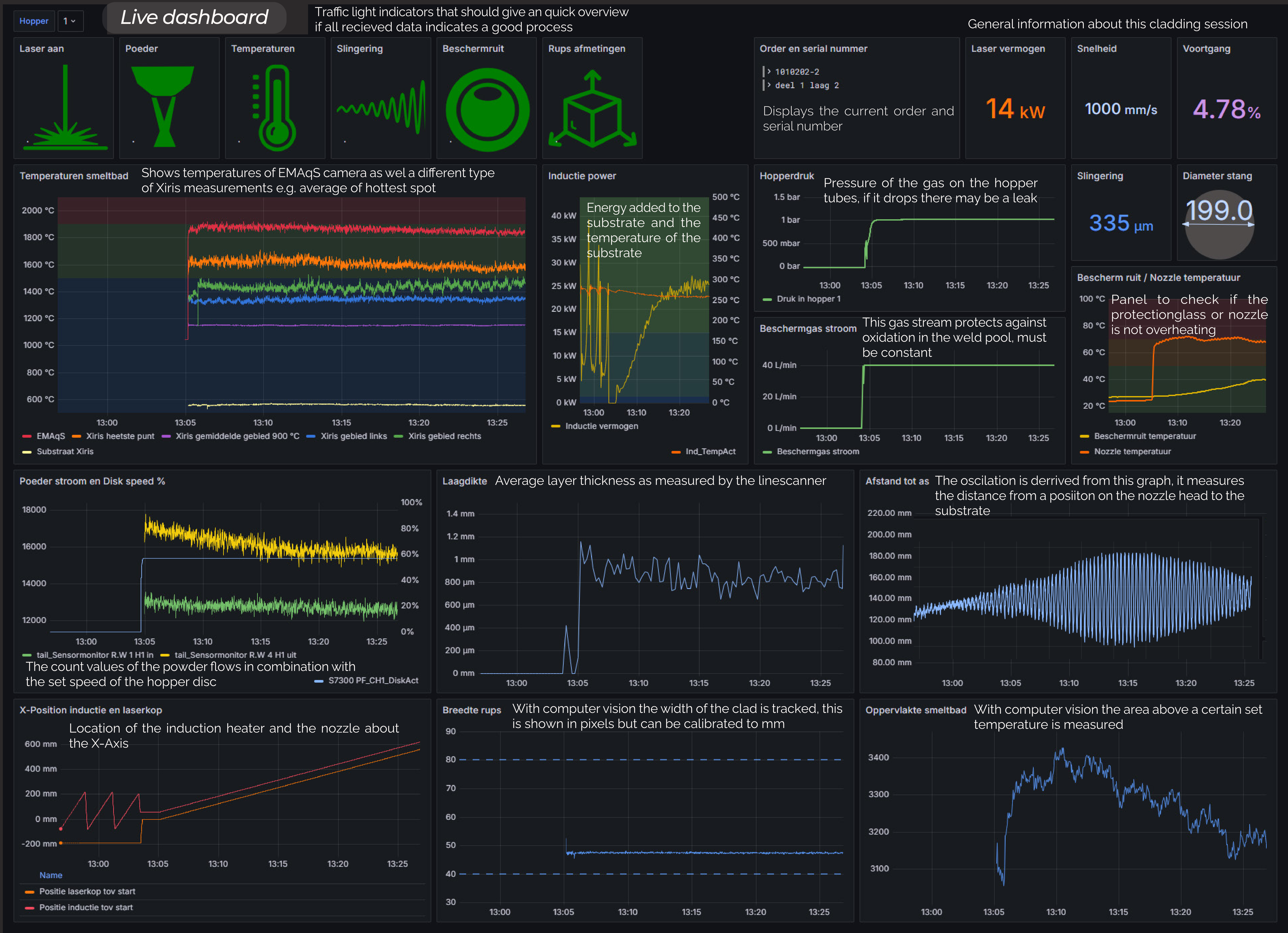
The primary function of this dashboard is to replace the physical logbook, eventually making searching for data faster and adding the ability to use the data in visualisations together with the other visualisations. There was already a physical logbook that the operator had to fill out, so the new digital logbook was derived from this form. However, now that the logbook is digital and more machine metrics are saved in a database, some of the machines outputs can be used to fill out a part of the logbook automatically. The production order and serial number are selected and automatically filled in. The diameter, disk speed, sales order, and timings are good examples of values that can be filled out automatically. The operator can then fill out the form with information about the sections he coats, and then the data will be saved in a separate bucket. This information can then be viewed in the dashboard, which is used to look up the logbook data. Here, you can see a list of entries in the logbook together with their times. If the order and serial numbers are known, one can select them and view the entry. An added functionality of having this data digitally and in the same database is that it can be displayed together with actual machine metrics. In this way, all the knowledge the company has about one rod can be displayed in the same place.

Quality feedback

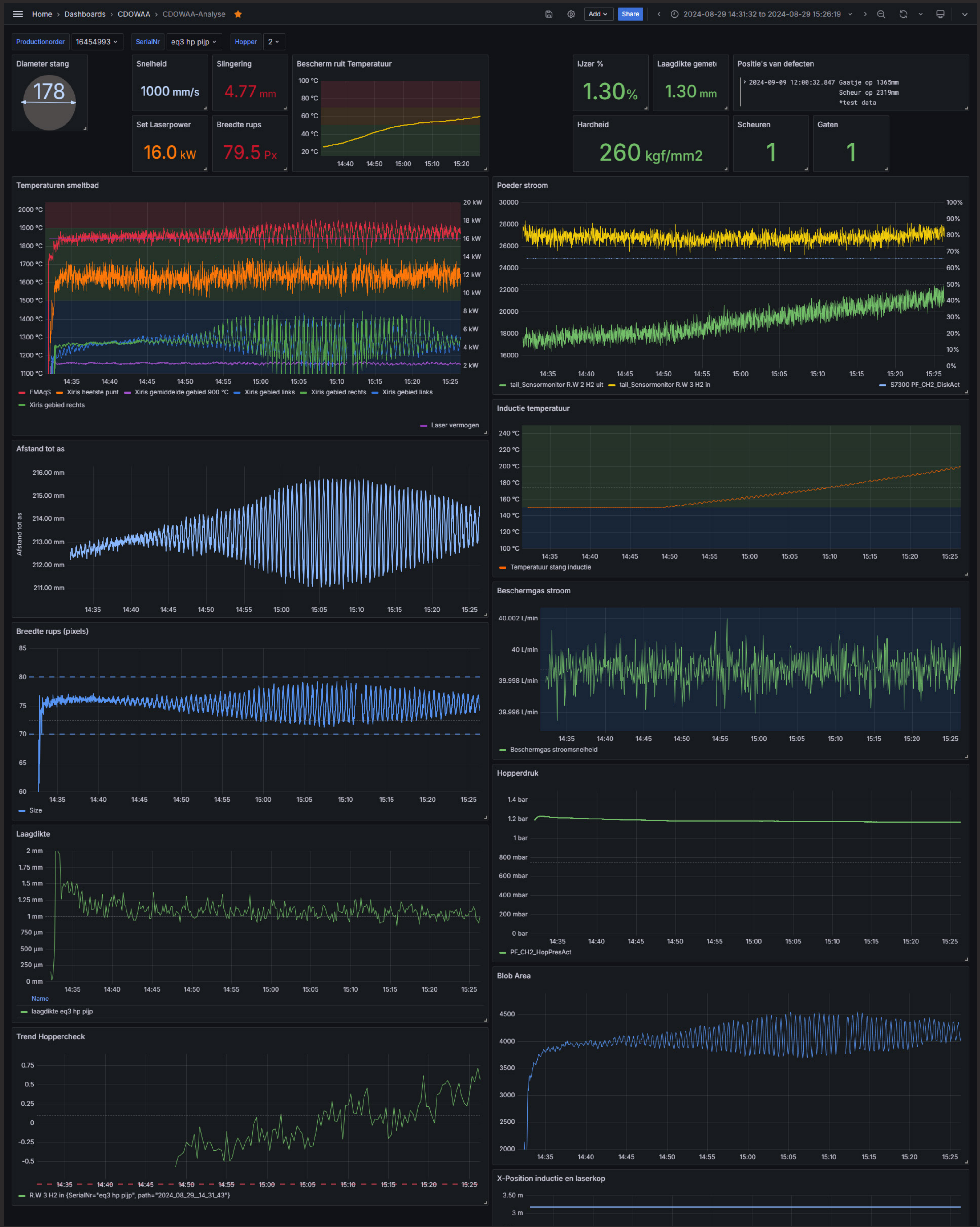
This logbook-like dashboard is used to input information about different production orders. This includes measured layer thickness, hardness of the HAZ, iron content percentage, the number of pits and cracks found, and their positions. The quality department could fill in the information after doing their tests.

Experimental dashboards

This dashboard is used to test new panels and ways to visualise data, and for research, when the new panel is helpful and working, it can then be copied and pasted into the dashboard that will benefit from this visualisation. One of the panels of this dashboard plots the location of the hot spots for any selected file. It could also be placed in the "onderzoek" panel where people can visualise certain relations, like a dashboard where the powder sensor reading was plotted against the hopper speed. This proved that the sensors were not good at consistently measuring the quantity of powder over different times.


Hopper
1
Live dashboard
Traffic light indicators that should give an quick overview if all recieved data indicates a good process
General information about this cladding session
Laser aan
Poeder
Temperaturen
Slingering
Beschermruit
Rups afmetingen
Order en serial nummer
> 1010202-2
> deel 1 laag 2
Displays the current order and serial number
Laser vermogen
14 kW
Snelheid
1000 mm/s
Voortgang
4.78%
Temperaturen smeltbad
Shows temperatures of EMAqS camera as wel a different type of Xiris measurements e.g. average of hottest spot
EMAqS
Xiris heetste punt
Xiris gemiddelde gebied 900 °C
Xiris gebied links
Xiris gebied rechts
Substraat Xiris
Inductie power
Energy added to the substrate and the temperature of the substrate
Inductie vermogen
Ind_TempAct
Hopperdruk
Pressure of the gas on the hopper tubes, if it drops there may be a leak
Druk in hopper 1
Slingering
335 µm
Diameter stang
199.0
Beschermgas stroom
This gas stream protects against oxidation in the weld pool, must be constant
Beschermgas stroom
Bescherm ruit / Nozzle temperatuur
Panel to check if the protectinglass or nozzle is not overheating
Beschermruit temperatuur
Nozzle temperatuur
Poeder stroom en Disk speed %
tail_Sensormonitor R.W 1 H1 in
tail_Sensormonitor R.W 4 H1 uit
The count values of the powder flows in combination with the set speed of the hopper disc
S7300 PF_CH1_DiskAct
Laagdikte
Average layer thickness as measured by the linescanner
Afstand tot as
The oscilation is derrived from this graph, it measures the distance from a posiiton on the nozzle head to the substrate
X-Position inductie en laserkop
Location of the induction heater and the nozzle about the X-Axis
Name
Positie laserkop tov start
Positie inductie tov start
Breedte rups
With computer vision the width of the clad is tracked, this is shown in pixels but can be calibrated to mm
Oppervlakte smeltbad
With computer vision the area above a certain set temperature is measured

Analytical dashboard



On the analytical dashboard, the user can select data from any desired combination of a production order and serial number (Figure 63). After doing this, a set number of graphs will show the selected data, just like in the live dashboard. This data can be a year old or can be an hour old.
The difference is that the quality and logbook can be filled during checks and cladding. This data can then be displayed in the same overview as the other data.
The live dashboard was made to fit the screen perfectly without having to scroll, always showing the traffic lights. Because the analysis is done on different screens and more data can be shown, this dashboard is scrollable.
There is also the possibility of plotting data against the logged position on the rod for analysis. This can be seen at the bottom of this page.

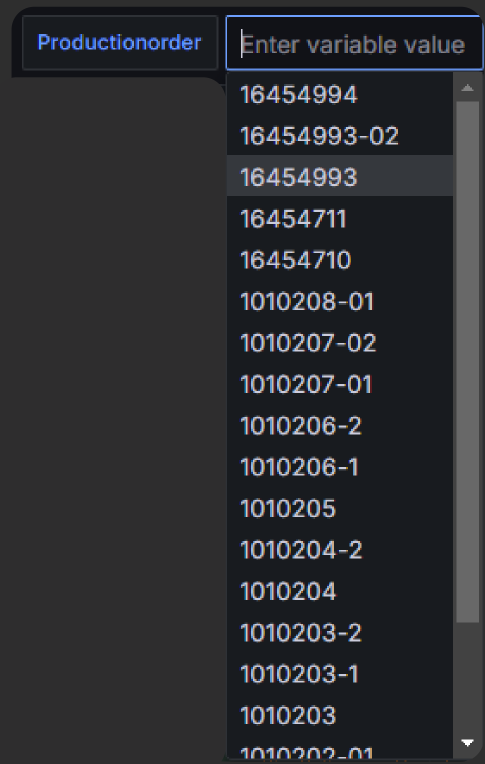
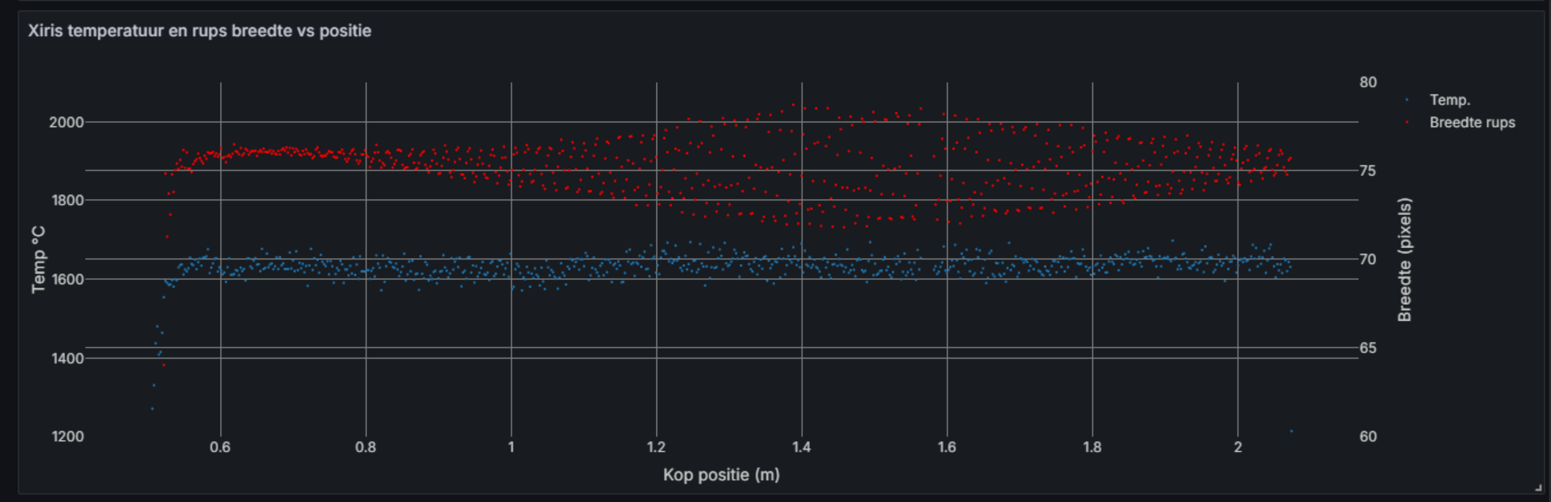


Figure 63 - Selecting a Order number and SerialNr



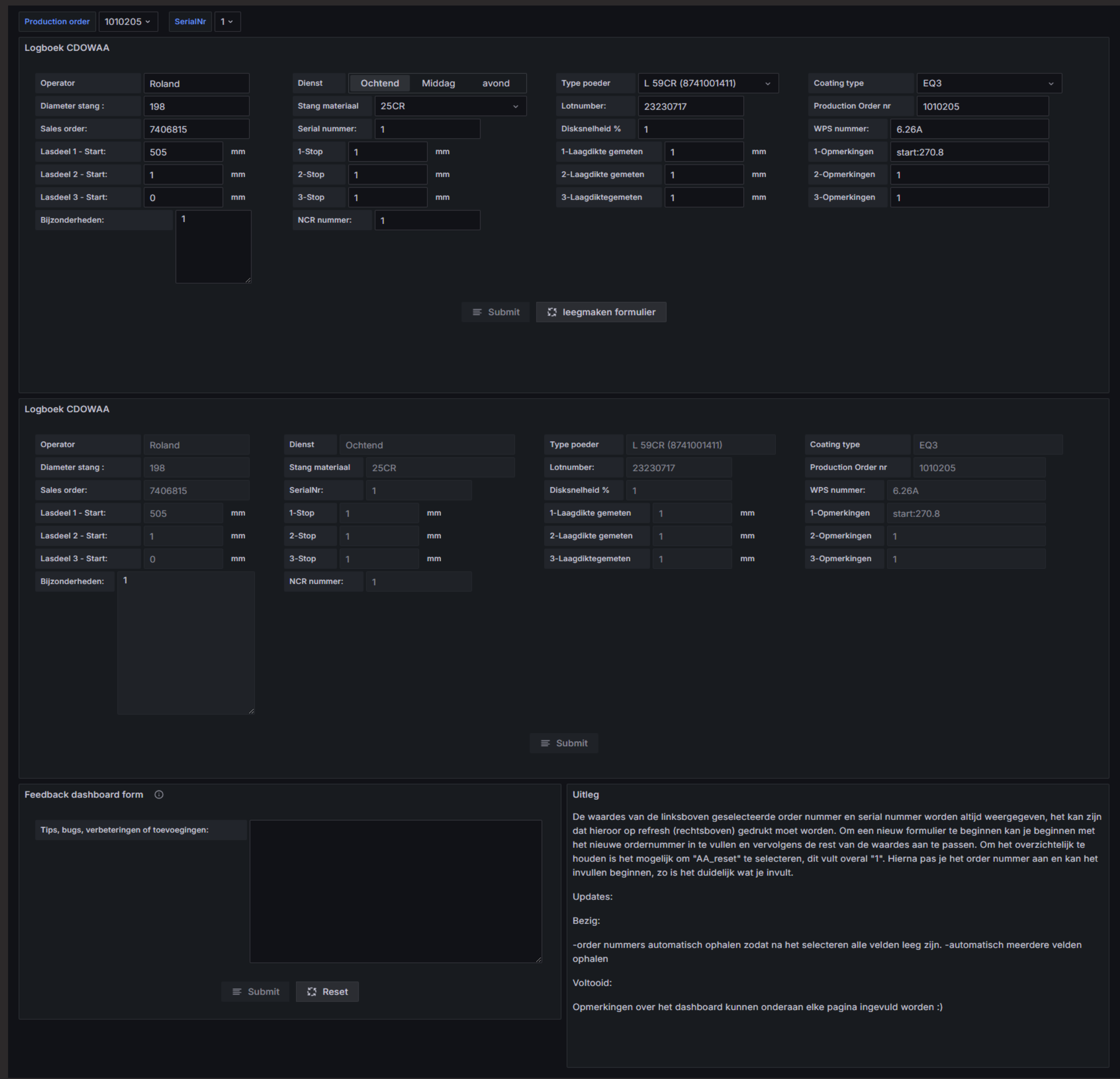
Comparison dashboard

To compare different processes the comparison dashboard is made. The user can select combinations of order numbers and serial numbers and then has the option to compare the data that was generated during the production of these layers. Laser power, scanning speed, layer thickness, and temperatures, are all values that can be compared from one case to another.

Logbook

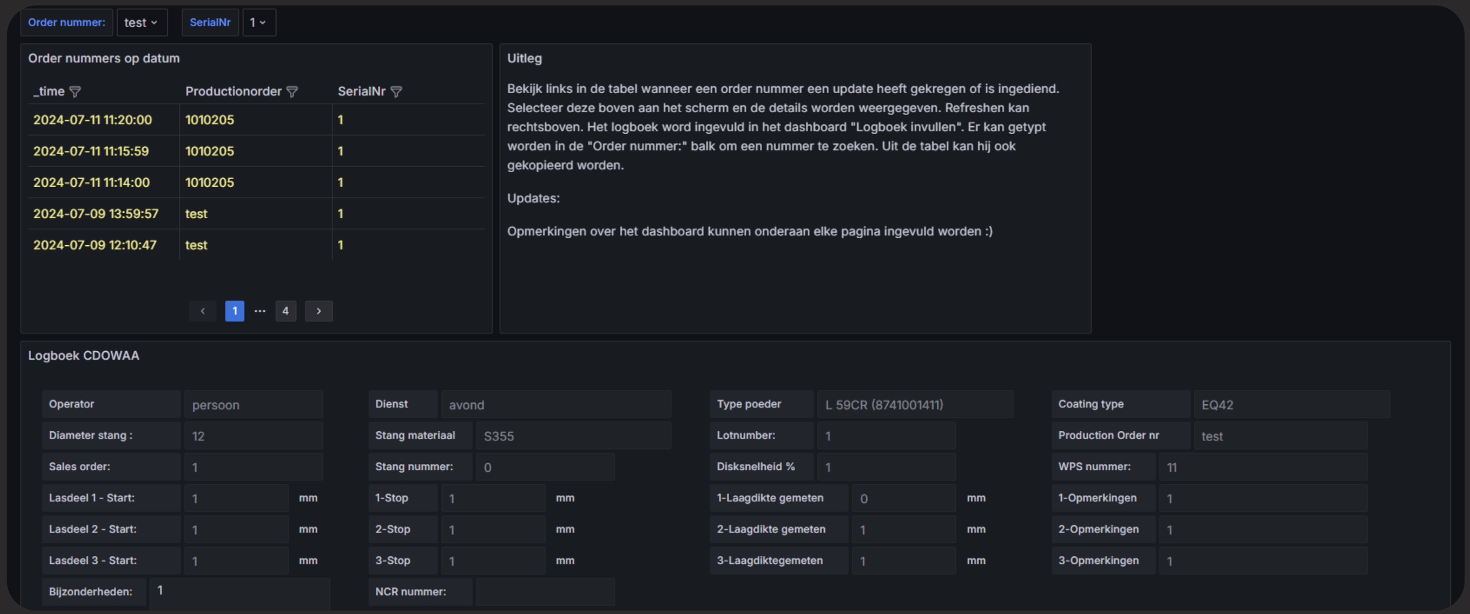
On the analytical dashboard, the user can select data from any desired combination of a production order an perfectly without having to scroll, always showing the traffic lights. Because the analysis is done on different screens and more data can be shown, this dashboard is scrollable.

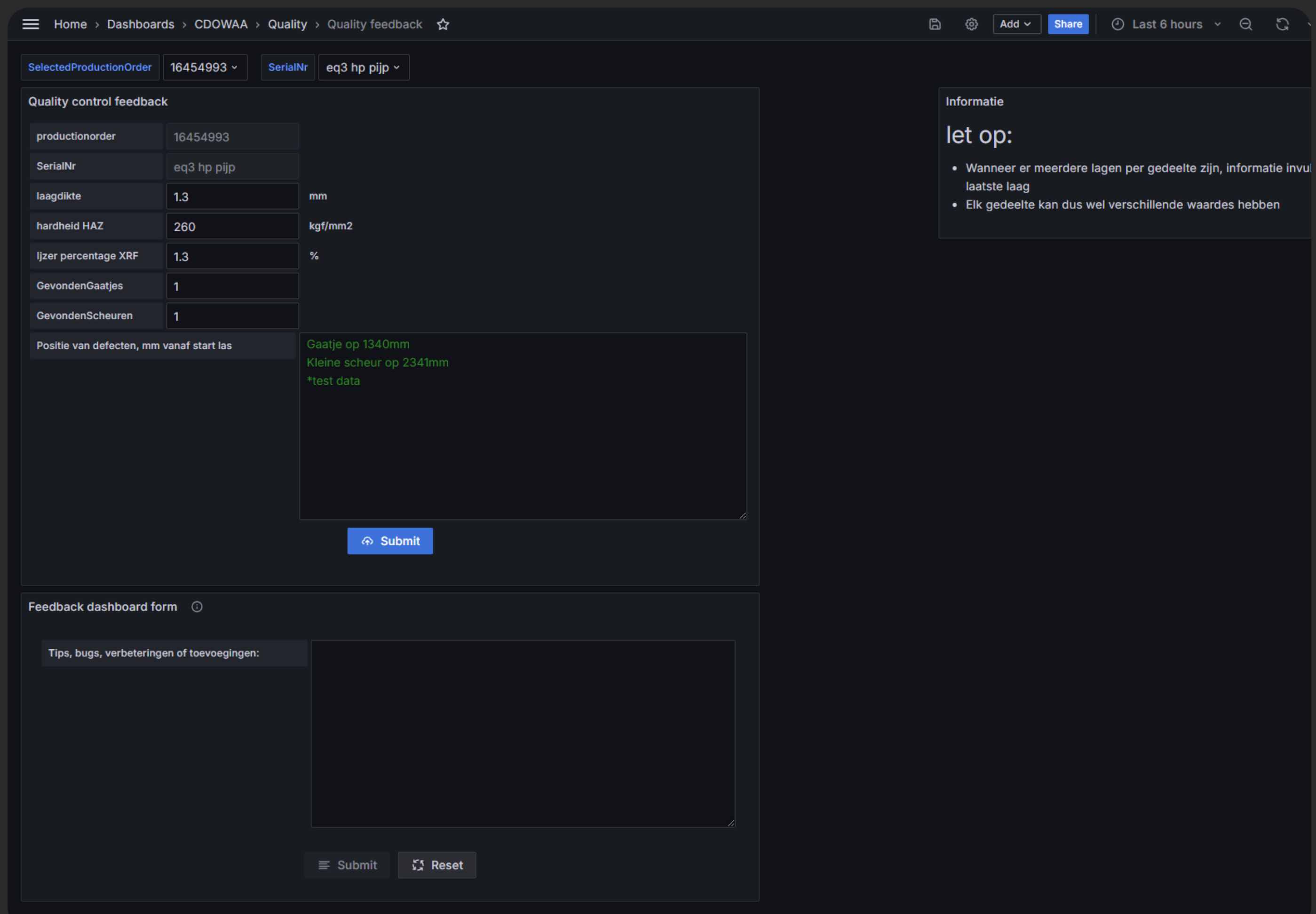
There is also the possibility of plotting data against the logged position on the rod for analysis. This can be seen at the bottom of this page.



Logbook and quality feedback

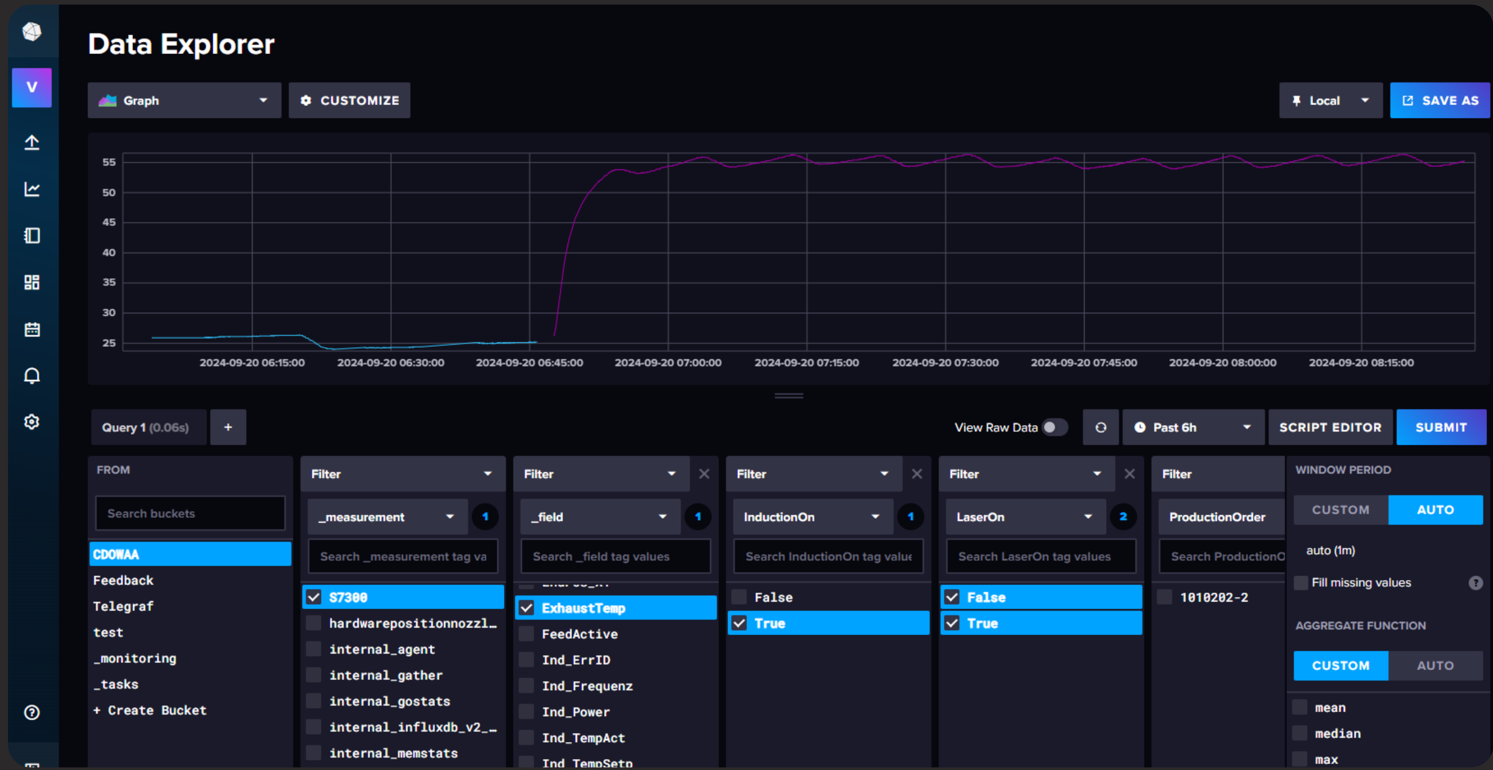
This page shows the dashboard where the logbook entries can be viewed and searched. The user can click through the recent entries or filter and search for specific times or order numbers. If the desired order number is found, it can be selected, and all the data entered under this order number can be viewed. The second picture shows the form that the quality department can fill out. The complete set of data can later be displayed together with the process data.





Database GUI

The database has an interface that shows what kind of data it has received and stored. This is helpful for understanding how data is stored in the database and how to query it for visualisation. The database is mostly a passive program that receives lines of data. These lines of data determine how the data is stored. In the database, retention times for data can be set, and some settings can be adjusted. However, deleting data and interacting with the database on a more technical level is done via a command line interface, config file or its API. The bottom code shows the current way of deleting all collected data from where the machine is turned off. In this case, all the data where both the laser and the induction spool are turned off will be deleted. This ensures that only valuable data is stored in the database.




```
$uri = "http://boxappl80.lp.lan:8086/api/v2/delete?org=Van Halteren Technologies - Boxtel&bucket=CDOWAA&precision=ns"
$headers = @{
    "Authorization" = "Token JLQIah_hZViqAHi4cEpKciff38lktX3kkQUajpuIt3IMSTCh2_9zUCzbMoLMfVdJjUjb1DYtkSch93CQ3t_Wiw=="
    "Content-Type" = "application/json"
}
$start = "2010-03-01T00:00:00Z"
$stop = "2026-11-14T00:00:00Z"

# Define the predicates
$predicates = @(
    '_measurement="modbus" and LaserOn="False" and InductionOn="False"',
    '_measurement="S7300" and LaserOn="False" and InductionOn="False"'
)

# Function to delete data with a given predicate
function Delete-Data ($predicate) {
    $body = @{
        start = $start
        stop = $stop
        predicate = $predicate
    }
    $jsonBody = $body | ConvertTo-Json
    Invoke-RestMethod -Uri $uri -Method Post -Headers $headers -Body $jsonBody
}

# Loop through each predicate and delete data
foreach ($predicate in $predicates) {
    Delete-Data $predicate
}
```

Dashboard data

Distance sensor data

The line scanner also outputs the distance from the sensor to the rotating rod. With this data, VHT can measure the rod's deflection. This rod is clamped between two pins on the two ends of the rod. Also, it is supported by rollers at a certain distance. This can be seen clearly in the data, at the start (near the roller or pin), the deflection is low. This increases until a maximum in the middle and starts decreasing again when the head is nearing a roller, and the rod is more stabilized. This deflection may not be too large because this distance will influence the melt pool, as many parameters fluctuate in the same frequency as this deflection.

A maximum of 3 mm was set as a maximum. In the analytical dashboard, there is a panel that shows the deflection (Max distance – min distance) for the selected range. The live dashboard takes the last minute as a range and displays the deflection value, which is used for the deflection traffic light. In this way, the user can quickly see if the deflection is within limits and can look up the deflection at any given time to input in production documentation. The timing should be correct to determine if the distance is positively or negatively related to the temperature (see timings). During testing, a rod was not centred well, and the deflection increased to a maximum of 4.76 mm. This oscillation could then be found back in the analytical dashboard, and the live dashboard showed this as a red traffic light. The result of this oscillation can be seen in the temperature data, clad width, and clad area. Making the process a lot less stable.

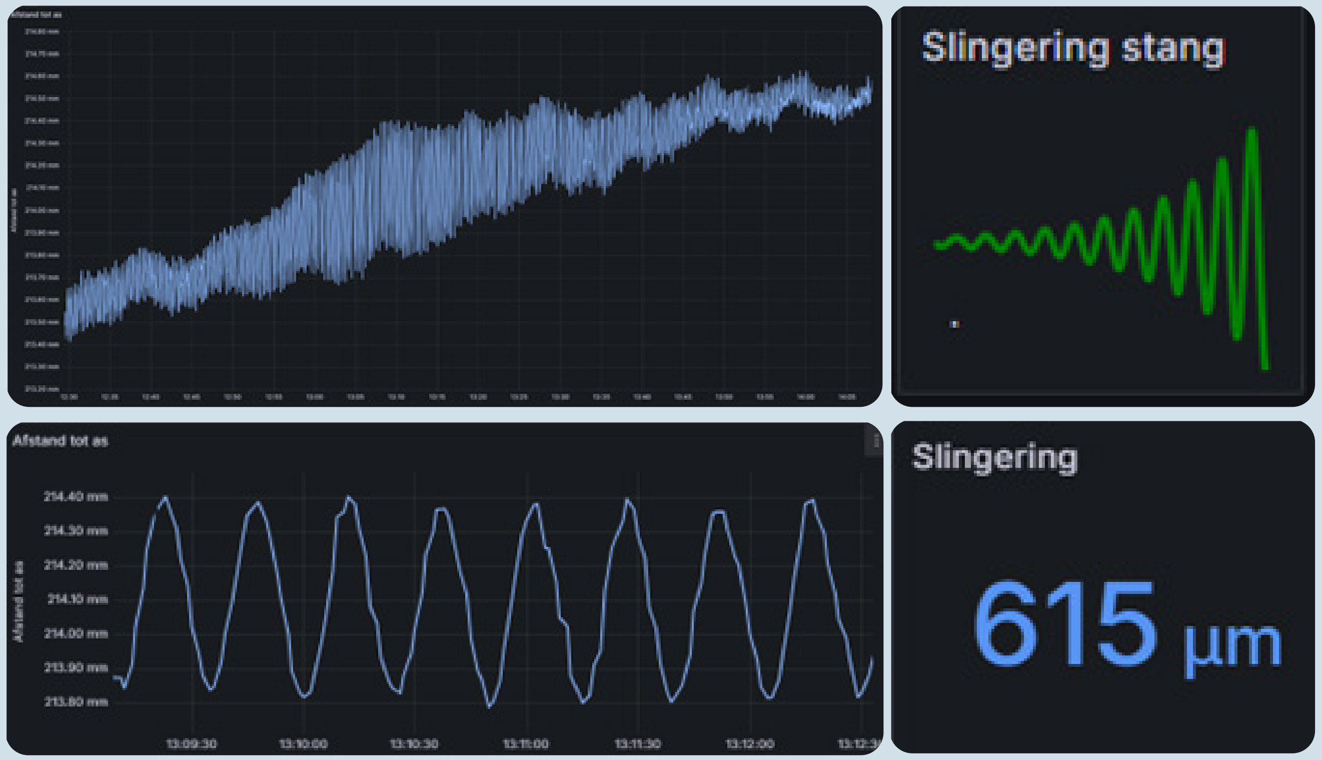


Figure 64 - How the dashboard displays the distance data, the traffic light alert and a way to quantify the deflection over a certain time

Clad width

The width of the welt pool should increase when the temperature increases, this is something VHT can see back in most data. The width is determined by the edges of the pool where the temperature gradient is the biggest as seen in the thermal camera. How the exact edge is picked depends on some parameters that should be kept constant to compare values. For now, the width is set in pixels, however, this can be calibrated in the software to mm. The hard part is that calibrating must be done with something visible for the thermal camera so with an object > 400 °C.

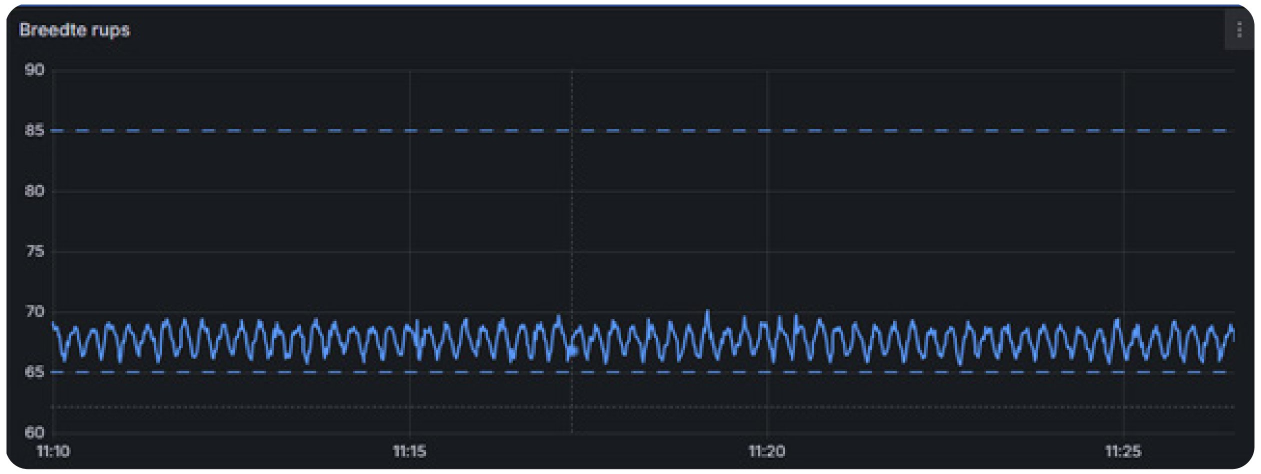
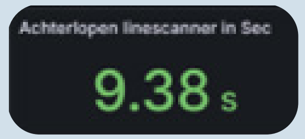


Figure 65 - Ocilating clad width as shown by dashboard and measured by Xiris software

Timings

The timing of all live data is set to the time of the pc that it processes, this timing is very precise. The timing of data that is stored in a file can also be very precise but it depends on the software that wrote the file. The camera software writes a very precise timestamp however, the Fraunhofer software does not write timestamps. It uses exact timings but needs to be converted with its file name this makes it so the timing could be 500ms late or early. This is not a big deal but something to keep in mind and fix if needed. This is possible when the start time from within the file is taken for the conversion, this was not as straightforward as the other method. The biggest time-related challenge is getting the clocks of the different PCs synchronized. As the PCs are not connected to the internet they can't update their time. What can be done is manually synchronizing the PCs with "Net Stat" on the command line. However, it was noticed that they would drift apart almost a second a day. This was solved by making it automatically synchronise.
All the data gathered can be compared in time, however, because the line scanner measures its profile at 90° to the cladding head these measurements can only be compared to what was cladded a few moments before. This difference can be calculated by :

$$T(s) = \frac{\pi * D * \frac{90°}{360°}}{v\left(\frac{mm}{min}\right) * 60}$$



For a rod of 199 mm and speed of 1000 mm/min with a 90° angle, this is 9,38 seconds. This means that when there is the need to compare the line scanner's layer thickness and distance the data needs to be shifted 9,38 seconds to the future. The diameter and speed are given in the data so this could be calculated automatically in the analytical dashboard.

Pre-heating data

In the snapshot above typical pre-heating data is shown it consist of data about protection gas flow, hopper pressure, and hopper disk speed. Also, cross-jet gas flow can be shown here however this airflow to remove powder does not work (yet) so is turned off in this display. At 13:20 two powder calibrations can be found. Here the powder flow is started for a minute and then the powder is weighed to set the required disk speed for the required grams per minute. So around that time the 'DiskAct' goes to around 60% together with the 'HopPresAct' at ~900 mbar and the ProtectGasFlow at 40L/min as expected. After which the actual pre-heating starts, this can be seen by the movement back and forth of the induction axis together with the induction power and the temperature ('Ind-TempAct').
The pressure and flow metrics are placed in different graphs, for now, to keep them apart better. The combined graphs are done for space efficiency and because they have less priority than some other values.

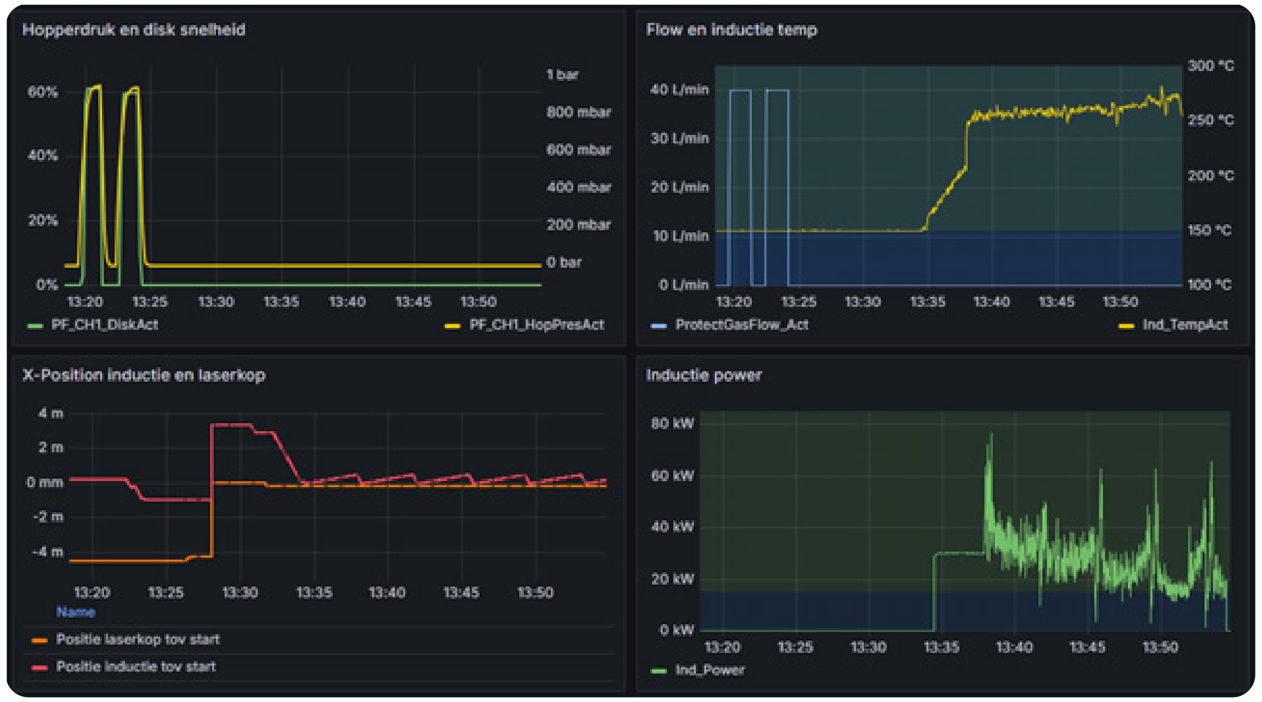


Figure 66 - Snapshot of data durign Pre-heating, showing power, temperature, speeds, pressures, locations and flo

Temperatures

One of the most important panels, apart from maybe the visual views, is the panel that shows the temperature of the different cameras. Two cameras can measure the temperature, the EMAqS from Fraunhofer and the Xiris infrared camera. The EMAqS has software that converts the camera view into one temperature. The Xiris camera has software that lets the user set their temperature measurements. For now, three different methods were chosen.

- The Xiris hottest point temperature, which is the mean temperature of a small area around the hottest point in the image.

- The Xiris average blob temperature, which is the mean temperature of the blob selected by the area that is above a certain area (in this case 900 °C)

- Two custom areas that can be positioned in the camera view, in this case, an area in the left and right section of the melt pool was chosen.

These temperatures together give the view one can see above, because of the different ways the temperature gets measured their averages can vary a lot. However, because of this they fit well together in one panel and give the user a broad overview of what is happening temperature-wise.
If an extra temperature measurement is desired, for example of the substrate, this can be added in the Xiris software and it will automatically show up in the Grafana dashboard.

Figure 67 - Different temperature measurements combined in a graph on the dashboard

13 Results

Now the dashboards are live and introduced to the team that deals with laser cladding at VHT, it can be seen how this impacts process insights and coating quality. The results of the introduction of dashbaords and the results of the literature research are found in this section.

Improvements in data insight, added functionality and users' opinions and experiences will measure the dashboards' influence on laser cladding at VHT. So, the results will consist of more objective elements and subjective opinions of the stakeholders. The literature review has been instrumental in identifying the critical process parameters that need monitoring. Combining it with knowledge and procedures at VHT sheds light on what defines a good coating for VHT and how users interact with interfaces.

Speed and ease of access

One of the most significant advantages of the new data collection and visualisation method is the ease of access to the data and the speed at which something can be analysed. It now takes seconds to graph specific data instead of over an hour, giving the process engineer more time to look at the data and compare it. Production needs to move on, so there is limited time to reflect on the data; getting a quick overview ensures more analyses are done in the same timeframe, finding interesting data that would otherwise not be seen.

Fault detection

The addition of a traffic light system has significantly enhanced the ability to view real-time quality indicators and add logic behind them to watch important trends. This system consists of green, yellow, or red indicators based on the processed data. While it currently only spots processes significantly off from the specifications, further tweaking and expansion will make it even more effective in giving an overview of whether what is happening will result in a good coating.

Insight

The increased speed and accessibility allows for more time to examine the actual data. This data is plotted the same way at all times, creating fitting visualisations. This makes it possible to open the browser and check the data after each rod is produced, in the old situation some data was only examined when problems were found.

Quality

The domain of quality has multiple aspects. The geometry of the coating should be as specified. This included having the right thickness and not containing holes or parts where the substrate was not correctly wetted. The coating's metallurgic properties should also be as described in the specification. Most importantly, there should not be too much dilution with the substrate. This increases with higher laser power and weld pool width and depth [19],[20]. Another factor is the hardness of the HAZ; this may not be too high; by increasing the preheating temperature and the energy input into the welt pool, this value is lowered. This is the first balance that needs to be found. The Xiris camera and experience at VHT have shown that the powder used should be high-quality and free of contaminants or slag particles that may cause pitting or holes.

Technologies and Hardware

During literature research, interesting hardware was identified that could possibly increase knowledge about the process at VHT, mainly the LiSec sensor from Fraunhofer and ultrasonic microphones. The LiSec, or a custom way of detecting the powder placement and geometry, is essential as it is one of the last unknown parameters in the cladding setup. The ultrasonic microphones can detect in real-time if cracks occur; this can warn the operator, via the dashboard, to stop the process. Lastly, a new and improved nozzle will be installed; offsets in this nozzle will be more straightforward to set and read. These offsets can now be logged in the logbook for each cladding session making this factor more insightfull.

ANNs

The trained and tested neural network could identify an incorrect process from a correct one. This program could run and send classification data to the database, communicating the state of the EMAqS pictures. This could then become an indicator in the dashboard. However, making the ANN as accurate as is needed for the dashboard would take much time, training and tweaking, so this was not done for this project. This is a good recommendation for future research.

Instruction operators

The operators interact minimally with the dashboard, as it displays information. The only buttons they may have to press are to change the time window and the displayed hopper. Some explanation has to be given for the logbook as this needs to be filled in a specific way. Also, information on the use of some dashboards is displayed on the dashboard itself to make it more self-explanatory.

Data insight matrix

In Figure 68, a weighted matrix compares the situation before and after the installation of the dashboards. This will more objectively judge whether the dashboards give more insight into the data than without it.

Data insight increase

Aspect / Criteria	Weight	Score "Before"	Weighted score	Explanation	Score "After"	Weighted score	Explanation
Historic data accessing speed	0.15	5	0.75	It took 0.5 to 1.5 hours to go to the machine, plug in a USB, find the right file/data, process it and put it in PowerBI or Exel.	9	1.35	From a known production number or serial number it takes seconds to graph the data required.
Real-time quality insight	0.15	5	0.75	The data can be viewed in real-time and there exist limits in the software	8	1.2	Data is analysed and if a metric is not within spec, an indicator turns red.
Accesibility data	0.15	2	0.3	Only with an USB an acces to the machine data could be copied an analysed on personal laptop.	8	1.2	With a simple browser login users have acces to all the gathered data
Logging and storing data	0.10	5	0.5	No quality data was logged in the same way any project. storage was done but not very accesable.	8	0.8	All data is stored by their order numbers in the database. An simple selection can select all the data in Grafana or Influx.
Comparability of data	0.10	4	0.4	Not all data was always stored, data contained different time columns making it hard to compare data.	8.5	0.85	All data is collected at synchronized times and can be compared in the same view together with custom notes or measurements. Data can also be compared to location.
Visualisation of the data	0.10	7	0.7	All options for data analysis could be used but not automatically.	8	0.8	Extensive plug-in support makes sure all visualisation can be made or programmed
Undertandable KPI's	0.10	4	0.4	None were given appart from the different graphs	7	0.7	Clear indicators can communicate the KPI's however the reliability of the KPI's can be improved.
Customization and flexibility	0.08	7	0.56	The default software of the sensors could only display the dat in one format.	8	0.64	The options of what to do with the data are expanded to anything that can be done with Python, Grafana and some other programming and data analysitc programs.
Responsiveness and speed	0.07	8	0.56	Original software does have almost no delay but can't interact with data easily	7	0.49	Data loads within few seconds and any 5 seconds the trends and data is updated.
Total score	1		4.92			8.03	The way data is communicated is increased significantly at VHT

Figure 68 - Weighted matrix to calculate score before and after the introduction of the dashboards

14 Discussion

Application on other cases

VHT is not the only company working with a laser cladding machine. It is also one of many companies working with complex machines that need monitoring and sensors. Especially if the machine has many added sensors, it would be helpful to recreate what was done during this thesis. This section will explain the things to look for and the possible challenges and pitfalls. The first step in the process is understanding the machine, the process that needs monitoring, the control systems and the communication protocols of all the sensors. Sensors and equipment all have their custom settings, software, and ways of communication (analogue, digital, ethernet, serial).
It was helpful to create a network and devices map to understand how the devices are physically linked and add all devices together. The network map of the Cladding machine made for VHT is found in the appendix under "Network map". This helped make the right decisions on how the information should be transferred and helped with internal communication at VHT. Depending on the available documentation on the sensors and the way it is installed, this first step could take some time and trial and error. If no live output is available but log files are written, with the right plug-in, it is possible to continuously poll this file for the added data (Telegraf tail plug-in). This is not optimal, but it had to be used for some sensors to extract data from them.

When the devices and communication channels were inventoried, they had to be analysed to decipher the communication protocols, gather them, store them, and eventually display the metrics. For this thesis, multiple software packages and hardware was considered; this can be found in "choice of software". The "TIG stack", Telegraf InfluxDB Grafana was chosen. Using this software it is relatively easy to add different information streams together. From logging files, Modbus or Siemens communication to system and IT information. Knowing how to write basic, "Python-like" code (Telegraf) and ways to query data from SQL and Influx databases will help a lot in this process. The software's online documentation is essential in this process [62], [74]. The next step is physically making the connections between the devices and setting up the communication. In VHT's example, a switch was installed, and one of the monitoring PCs was granted access to the internal network. In this example, a minimum of extra hardware was needed, including only a few ethernet cables, ethernet-to-USB dongles, and a switch. When creating such a connection at a company, the IT department will monitor and manage the networks. Getting the right permissions, connections, and ports open, could take some time, this needs to be taken into account. Having the network map helps explain the connections and changes that have to be made to the people involved. When the connections are made, and information can be gathered, the processing, aggregation and storage of data can be arranged. It is important to know what will be collected and how the data will be used. The data can have multiple types: strings, bools, integers, floats and more. To use the data correctly, this should be specified in the code, or data should be converted into the right type. Then, intervals and labels should be added to the data. In the case of InfluxDB, data is stored with different attributes, "_Time", "_measurement", "_Tag" and eventually the "_Field". The way the tags are structured is essential to ensure the user can query the correct data later in the process, as the data is only related to time and, not automatically, to other metrics. The data also should have a precise timestamp. Because some systems were not directly readable without editing complex PLC programs, data had to be read from output logs. The timestamps in these logs sometimes needed processing to be used in InfluxDB because they counted things like the ms since the creation of the file. Here, the time had to be extracted from the filename and converted to ms since the epoch (Unix time) and the individual metrics, ms time had to be added to this, and eventually, this new time needed to be converted back to a time string. To create a stream of correct and usable information, multiple of these tricks needed to be used. This can be read in the explanation of the code. If Telegraf is configured correctly, the InfluxDB will now be filled correctly in a way that makes it possible to search for specific historic data.

The way to set up this Telegraf, InfluxDB connection is well documented and can be found on the software's websites and forums. Information about Telegraf was most helpful on GitHub. In VHT's case, the two servers for storing and displaying data (InfluxDB and Grafana) are accessible to any employee with the correct login. This means that the visualisations are now easily accessible to anyone that needs to have a look at it.

In Grafana, data can be displayed using multiple panels. If the panels do not provide the desired visualisation, plug-ins can display it in a wider variety of ways. If a completely custom visualisation is needed, a preferred coding language can be used to program it within Grafana. The visualisations are explained in Chapter 10. Now information is collected and visualised, it can be used to spot relations between variables, errors in production, the state of the machine, or the state of the process. This is where the logic part will be important. In the dashboards, logic can be written that controls certain indicators (traffic lights). This can simplify the interpretation of the data and be an objective limit at which the process needs to be adjusted or stopped. The logic written for VHT is explained in the "logic" chapter. When the same process described here is applied to another process or machine, a lot of flexibility is added to the ways the data can be visualised. It will also increase the speed and ease of analysis. In general, it will create more insight and control over the process.

Maintenance and future work on product

Maintenance is an essential part of the software life cycle [75]. This is why, during the project, the maintenance and future work that is needed on the product was taken into account. The delivered dashboards would need to be maintained and edited by someone to be kept functional. This was one of the reasons straightforward software packages were used instead of programming custom software or Python code. Also, the company's software engineer's involvement was vital in ensuring someone can maintain the dashboard. This makes it also possible for VHT to add and change features and add graphs when needed. This makes adding additional "traffic lights" or other logic and visualisations possible. In the future, additional sensors may be installed at VHT. Adding this new data to the database will be possible because of the software, its documentation and the knowledge within the company. This combined with the knowledge on how the database and Grafana works makes it so the product can also be used after the conclusion of this thesis.

Product discussion

Setting up similar data visualisation dashboards can help companies get more process control without hiring software developers who will write custom software for their specific machines. Someone who is knowledgeable about computers and has the time to read the freely available documentation about the software can complete the tasks needed to create such dashboards. The results of this thesis could make tackling such processes easier; however understanding the code will be most helpful. This ease of use is mainly possible because of the chosen software and the many ways to adapt it to a user's specific situation, which helped extract the needed information from files and data streams. It will also help when additional sensors are added.

The dashboard's efficacy depends on the quality of the information and the logic behind the indicators. If the data is inaccurate, the dashboard will be inaccurate, too. The powder sensor and the layer thickness sensors shown on the dashboard are not the most accurate or need further calibration. This possibly makes the accuracy of this data insufficient to spot the causes of some of VHT's problems.

The exact distribution of the powder and its location relative to the melt pool influences the melt pool and catchment efficiency [72]. This distribution can even change by varying the gas flow [71]. However, it is not measured and logged at VHT, which may be necessary to get a more complete picture of the process state. Cladding is a process with many paramenters making it hard to control all parameters [76].

Data visualisation is like a bridge between data and its understanding [77]. While the current dashboard effectively presents all existing data with added time relations, it must evolve to detect some of the problems VHT is grappling with. To address these issues, a deeper understanding of this data is crucial, perhaps with better sensing. This understanding was deepened during this project by making the data accessible, visable and installing additional cameras. With the complete information set in front of the process engineer, more relationships between inputs and outputs are likely to emerge. However, this will require more systematic testing and reviewing of the data in the dashboards. When there is a deeper understanding, this can lead to more intricate logic that can be built into the "traffic lights", making them more effective as key performance indicators. It can also lead to the need for additional sensing capabilities.

The interpretation, logic, and visualisation should align with the physics behind the process. The goal was to create intricate logic that could spot problems and slight variances in data that could indicate problems. However, by analysing the collected data, it became evident that a lot more than setting up limits and analysing trends is needed. A much deeper understanding and level of logging settings and logging the physical state of the machine is crucial.

Currently all data is collected in one database and tagged under the correct order number, which makes it possible to train an AI on this data. For example, the process data can be used as inputs and quality measurements, such as holes, cracks, hardness, and iron content, as training outputs. In this way, the ANN could predict the quality outputs using live process data. If this quality deteriorates, there is known that the inputs are not optimal according to the trained ANN. This training can be done reasonably cheaply with existing ways to set up these kinds of neural networks. However, creating a suitable dataset from the collected data and setting up the correct configuration of an ANN will be a long process. Using existing training data from other LC machines or simular processes can be beneficial [73].

Gathering more data just to gather more data can help, but it can also confuse. The question that needs to be asked is: Why is this data necessary? Too much data will become too complex. Accurate and concise data is more valuable than data with much noise or measuring an unrelated process. For example, during the exploration phase, some data was analysed, from which the conclusion had to be made that this data did not indicate that something changed during cladding, although something went wrong during this session. Indicating that somthing happend that is unrelated to the things that were measured.

15 Conclusions

There is a clear set of requirements regarding the quality of the coating. It must be applied well without cracks, pitting, or dilution and with the correct hardness for its application. Also, corrosion tests ensure it won't rust during its lifespan. The results of these tests can be quantified and logged in the new dashboard. Having this logged data in combination with the newly combined process data opens up more options for better insight.
The weighted matrix concludes that VHTB's new infrastructure and dashboards have vastly improved its insight into the collected data. Although it is hard to prove that fewer quality problems arose after the introduction of the dashboard, there are examples of specific problems, like a leaking powder tube or impurities in the powder, that can now be spotted or spotted quicker with the use of the dashboard. Future hardware like sensors can be easily added to the dashboard, improving it over time.
It was observed that different engineers, that have a stake in the LC machine, are using the dashboard regularly to check data and keep an eye on the process. This indicates that the dashboards adds value for them in comparison to using the methods used before.

Now there is a straightforward overview, additional sensing hardware can be beneficial. The last parameters that are not shown or measured yet can be added to the existing data, such as the hardware that logs the powder cone geometry or the exact rotational speed of the rod. With the ultrasonic sensors, the ability to give an early warning regarding cracks is added. Existing hardware can also be upgraded to more reliable sensing capabilities, like more accurate layer thickness scanners or powder flow sensors. This will improve the dashboard's effectiveness and the LC machine's reliability.

While quality monitoring is critical, prevention is better. The key is to learn from data, know what to look for in the future, and adjust the machine and its parameters to prevent new quality problems from occurring.

ANNs can be trained on gathered data. They are most effective for going through a lot of data continuously. However, they will not quickly be able to spot more than the operator. This depends on the training method, and creating a good enough ANN is possible but this requires additional time and resources.

The right software was instrumental in overcoming technical challenges and creating a functional dashboard within the given time frame. This software struck a good balance between customisation options and ease of use. Technically, the challenges of setting up such a dashboard lie in knowing the hardware infrastructure and communication protocols used in the system that needs monitoring. When this knowledge is available, only a few resources are needed to create such dashboards—a server and network connections are all that is needed.

Instruct operators clearly and concisely and structure the information. However, most importantly, make sure the interface speaks for itself. Creating many iterations and receiving feedback can help in this process. The feedback helped to increase the functionality and the ease of use. Design elements that did not make sense to the operators or the engineers were changed accordingly.

In conclusion, improved data collection and visualisation improve insight by ensuring the right person has quick and easy access to the complete set of information. This set consists of process data combined with the resulting quality feedback and the operator's notes. This complete set of data should be comparable by time and order numbers. This improved insight will ensure quality problems can be spotted better during production, especially when the traffic lights are used and the logic behind it is developed further.

16 Recommendations

The dashboard's development is ongoing, and additional warnings and logic can and should be incorporated to enhance its utility. For example, logic can be implemented to monitor hopper pressure and ensure it aligns with the powder flow. This could help detect leaks; this additional logic can be integrated into the "powder" indicator. Over time, as more of this intelligent logic is built into the system, the dashboard will become increasingly sophisticated and provide more valuable feedback to operators.

Introducing new sensors represents an important opportunity for gathering additional information and unlocking new insights. With the current database and visualization software setup, adding sensors is a relatively straightforward process. For instance, an ultrasonic microphone to detect crack formation could help prevent issues by halting cladding if cracks are detected. Additionally, incorporating a device that measures powder geometry, such as a LiSec, would address a significant unknown in production. Further powder sensor calibration and testing are required to improve their reliability and usability.

Exploring methods to enhance the accuracy of layer thickness measurements is another area for potential improvement. Research into alternative approaches to measuring this during production could lead to more precise control over the resulting coating.

A system for creating test order numbers with corresponding serial numbers in the dashboard would streamline testing and data tracking. Operators and engineers can quickly review past tests and their relevant data by logging a description of each test in the logbook. This feature would provide a selectable overview, simplifying the process of analysing results based on specific settings or parameters.

Logging the nozzle's height and offsets in relation to the laser in the logbook will also aid in data analysis and troubleshooting. This information should be readily accessible when reviewing historical data to identify issues or optimize performance. A calibration plate for the new camera should be introduced to improve calibration further, displaying the offsets directly on the camera.

For precise laser calibration, it is recommended that the laser be pulsed on clamped plates within the machine to determine its exact position relative to the solid ground. This will provide a reliable reference point for future adjustments.

Lastly, advancing operator training as was one of the first idea's can be a focus moving forward. Providing operators with the necessary knowledge and skills to interpret data, respond to warnings, and adjust settings will maximize the system's potential and ensure smoother operations. Comprehensive training will enable operators to leverage the full capabilities of the dashboard and associated systems, leading to improved productivity and reduced downtime.

These steps, including further dashboard development, sensor integration, system calibration, and operator training, will contribute to a more efficient and intelligent production process and allow for more precise monitoring, analysis, and decision-making.

17 References

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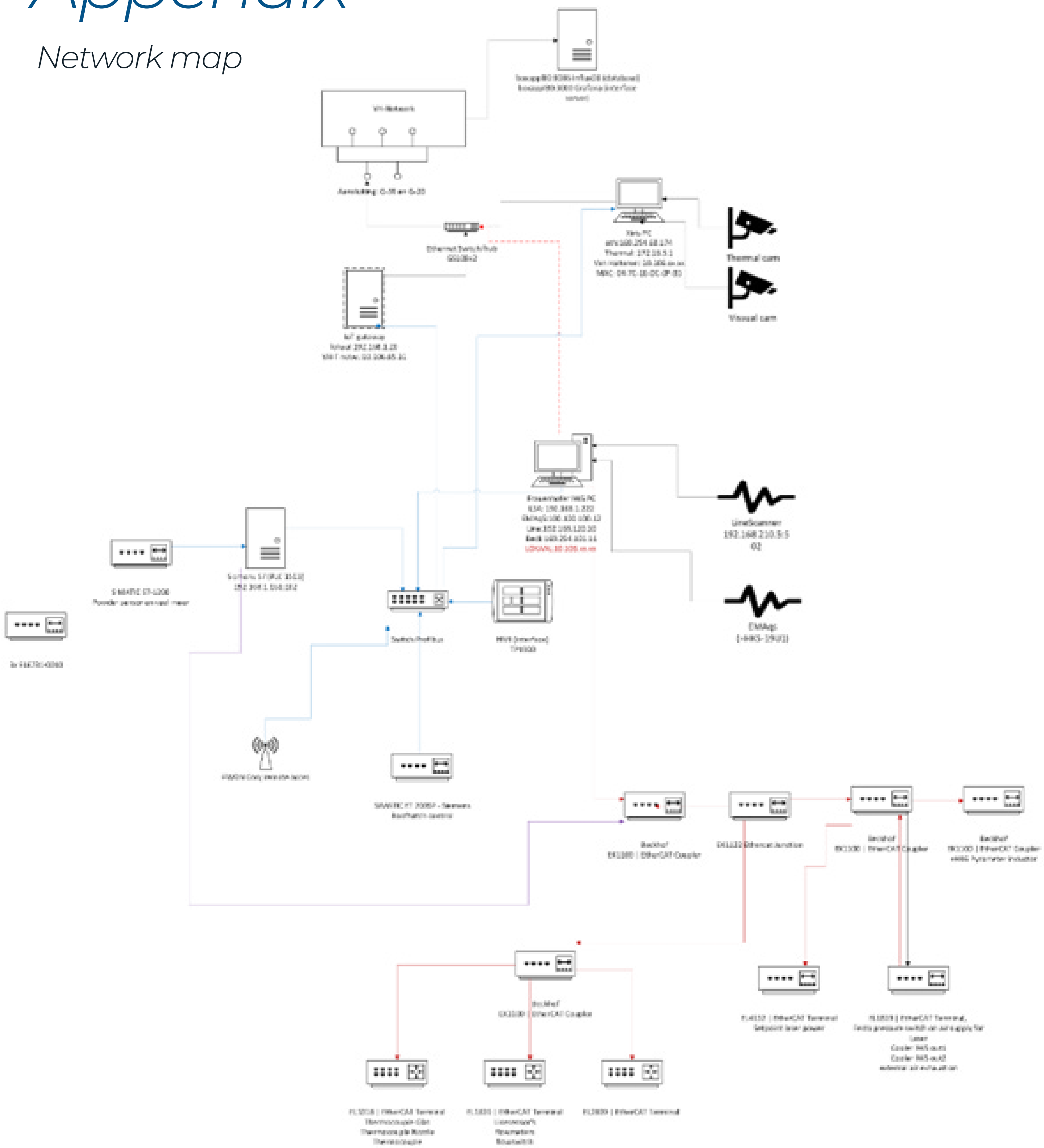
18 Appendix

Network map



Sensor parameter list

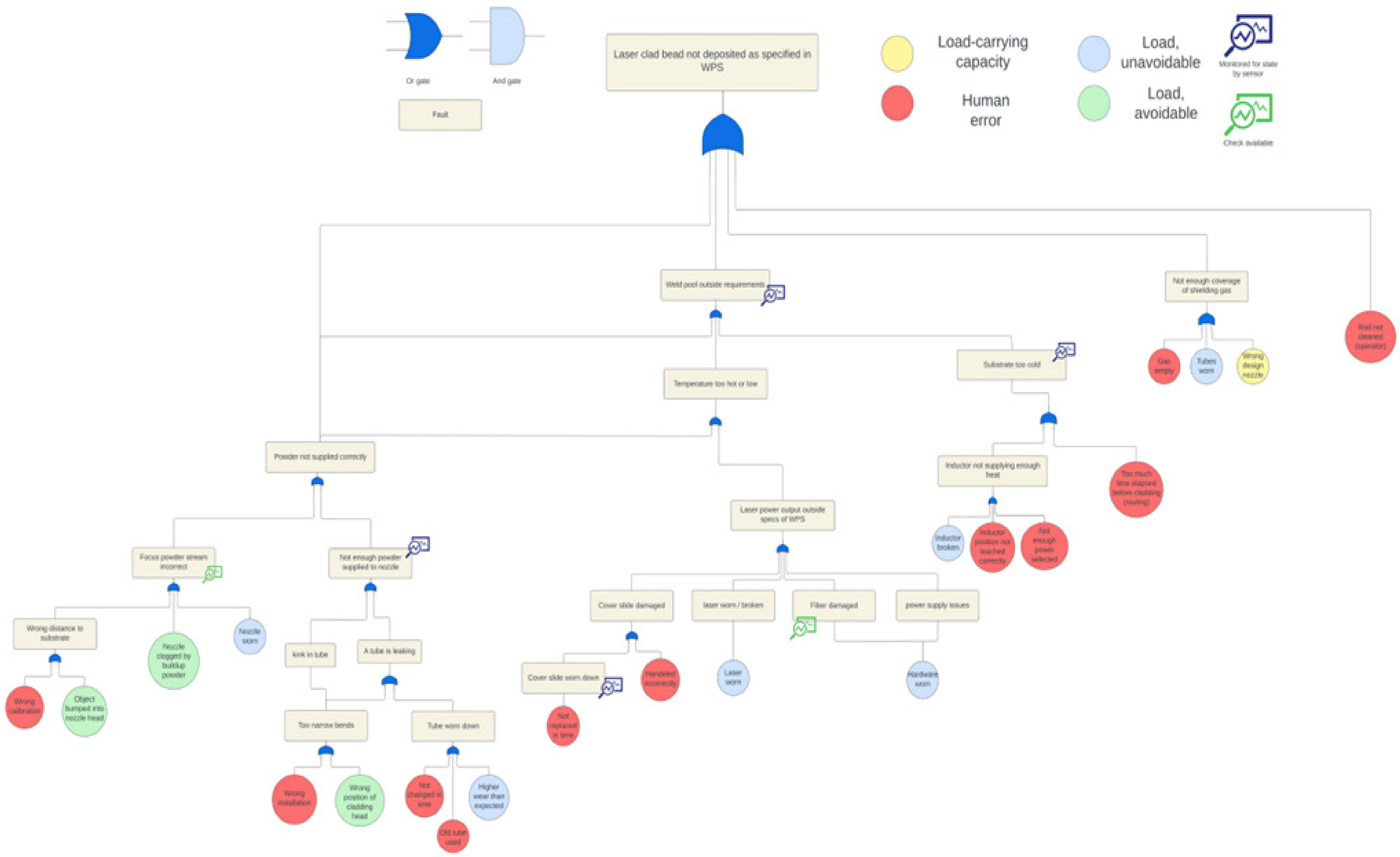
Input parameters	Imp.	Process parameters	Imp.	Machine Status
set speed		Average meltpool temp (Xiris)	9	ProtectGlasTemp (naam database aanpassen)
Set laser power		Average melt pool temperature (emaqs)	8.5	ReceipNr
Ind_TempSetp		Clad width (Xiris)	8	ProductionOrder
ProtectGasFlow_Setp		Hottest spot temp (Xiris)	8	SalesOrder
RodDia		Area of meltpool (Xiris)	8	SalesOrderPos
Ind_Frequenz		layer thickness	8	SerialNr
CrossjetGasFlow_Setp		R.W 1 H1 in	7.5	TimeToEnd
Ind_Power		R.W 2 H2 uit	7.5	TimeLeft_Tube2_PFtoSwitch
Ind_Waterflow		R.W 3 H2 in	7.5	TimeLeft_Switch1
Ind_Watertemp		R.W 4 H1 uit	7.5	TimeLeft_Switch2
ActPos_X1		Pyro. temp.	7	TimeLeft_Tube_SwitchToNozzle
ActPos_Y1		Ind_TempAct	7	TimeLeft_Nozzle
ActPos_Z1		Deflection over one rotation	7	TimeLeft_PF_CH1
ActPos_X2		Actual power to laser module	6.5	TimeLeft_PF_CH2
StartPos_X1		Nozzle temp.	6	TimeLeft_Protectionglass
EndPos_X1		Exhauast temp.	6	SpindelTurning
		Link to picure locations local pc	5.5	LaserOn
		PF_CH1_DiskAct	5	MachineOn
		PF_CH1_StirrerAct	5	InductionOn
		PF_CH1_HopPresAct	5	PF_CH1_Active
		PF_CH2_DiskAct	5	PF_CH1_Starting
		PF_CH2_StirrerAct	5	PF_CH1_Stopping
		PF_CH2_HopPresAct	5	PF_CH1_Running
		ProtectGasFlow_Act	5	PF_CH1_Warn
		CrossjetGasFlow_Act	5	PF_CH1_Err
				PF_CH1_ComOK
				PF_CH2_Active
				PF_CH2_Starting
				PF_CH2_Stopping
				PF_CH2_Running
				PF_CH2_Warn
				PF_CH2_Err
				PF_CH2_ComOK
				PF_ModeSer
				PF_ModePar
				PF_Ready
				PF_Busy

Safety parameters	Imp.	Progress	Imp.
Dust Monitor		PercentDone	
Nozzle temp.		ActPos_X1	
Exhauast temp.		StartPos_X1	
		EndPos_X1	

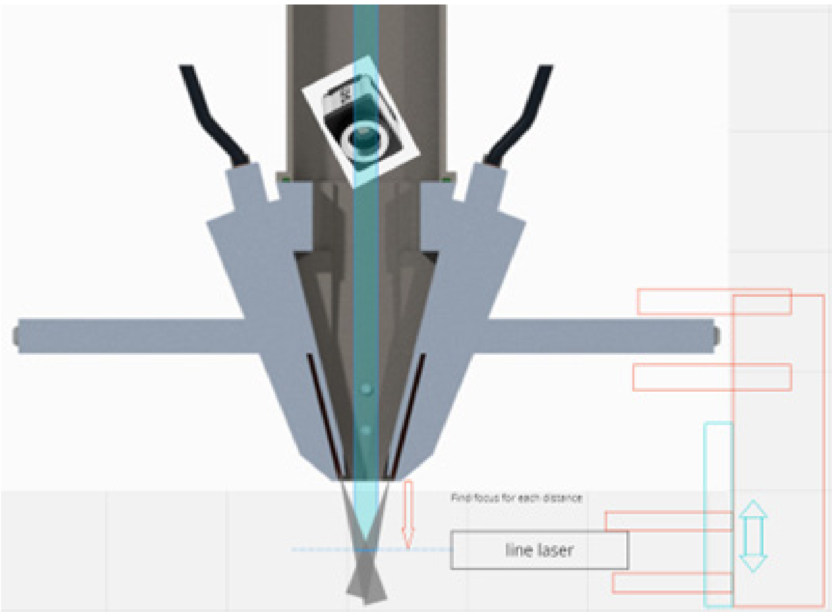
Beschikbaar:
In SQL database (via IOT)

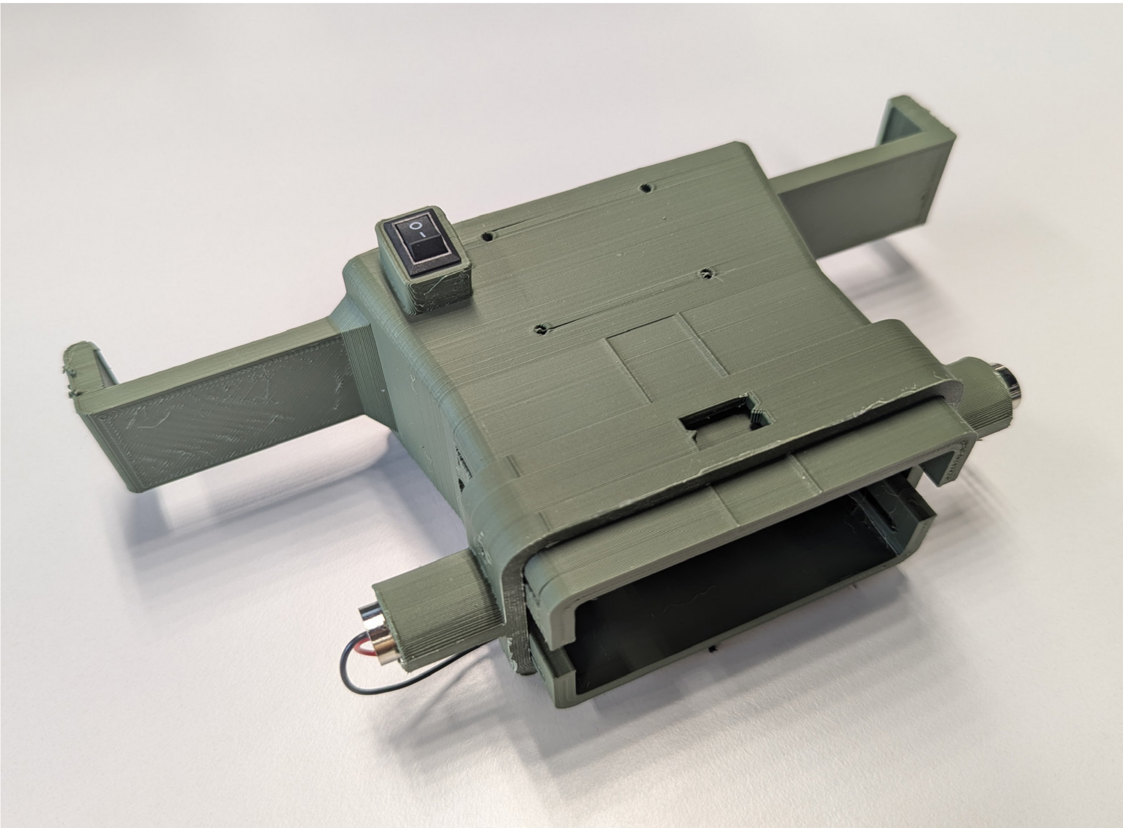
Niet beschikbaar:
Toe te voegen aan database VHT (SQL/influxDB)
No access (Fraunhofer nodig PLC)
nieuw, toe te voegen aan database
Makkelijk toe te voegen, nog niet belangrijk

Fault three


Or gate
And gate
Fault
Laser clad bead not deposited as specified in WPS
Load-carrying capacity
Human error
Load, unavoidable
Load, avoidable
Monitored for state by sensor
Check available
Weld pool outside requirements
Not enough coverage of shielding gas
Rod not cleaned (operator)
Gas empty
Tubes worn
Wrong design nozzle
Temperature too hot or low
Substrate too cold
Powder not supplied correctly
Inductor not supplying enough heat
Too much time elapsed before cladding (routing)
Laser power output outside specs of WPS
Inductor broken
Inductor position not teached correctly
Not enough power selected
Focus powder stream incorrect
Not enough powder supplied to nozzle
Cover slide damaged
laser worn / broken
Fiber damaged
power supply issues
Wrong distance to substrate
Nozzle clogged by buildup powder
Nozzle worn
kink in tube
A tube is leaking
Cover slide worn down
Handeled incorrectly
Laser worn
Hardware worn
Not replaced in time
Wrong calibration
Object bumped into nozzle head
Too narrow bends
Tube worn down
Wrong installation
Wrong position of cladding head
Not changed in time
Higher wear than expected
Old tube used

Powder focus check device design





Grafana / Telegraf code

The code displayed below is the code that is running on the Xiris PC for the collection of the Xiris and Siemens S7 data and to relay the data from the Fraunhofer PC to the database.

```
[agent]

  interval = "10s"

  round_interval = true

  metric_batch_size = 5000

  metric_buffer_limit = 20000

  collection_jitter = "0s"

  flush_interval = "10s"

  flush_jitter = "0s"

  precision = ""


[[outputs.influxdb_v2]]

  urls = ["http://boxappl80.lp.lan:8086"]


  token = "$INFLUX_TOKEN"

  organization = "Van Halteren Technologies - Boxtel"


  bucket = "CDOWAA"


[[inputs.tail]]
  files = ["C:\\Users\\joribrek\\Documents\\Files to database\\hotcold\\*.csv"]
  from_beginning = false
  character_encoding = "utf-8"
  data_format = "csv"
  csv_header_row_count = 1
  csv_column_names = ["Date Time", "Elapsed Time", "Frame Number", "X", "Y", "Min", "Max", "Mean", "MeanTemperature"]
  csv_column_types = ["string", "string", "float", "float", "float", "string", "string", "string", "string"]
  csv_delimiter = ";"

  csv_timestamp_column = "Date Time"
  csv_timestamp_format = "2006-01-02 15:04:05.000"
  name_suffix = "_HotCold"

  [[processors.strings]]
    tagpass = ["path"]
    [[processors.strings.replace]]
      field = "path"
      old = "\\"
      new = "\\\\"


[[inputs.tail]]
  files = ["C:\\Users\\joribrek\\Documents\\Files to database\\blob\\*.csv"]
  from_beginning = false
  character_encoding = "utf-8"
  data_format = "csv"
  csv_header_row_count = 1
  csv_column_names = [
    "Date Time", "Elapsed Time", "Frame Number", "Area", "Cx", "Cy", "X", "Y", "Width", "Height", "Perimeter", "FormFactor",
    "Orientation", "Eccentricity", "EulerNumber", "HoleCount", "TouchesBorder", "FeretDiameter0", "FeretDiameter90",
    "Compactness", "GrayMass", "GrayMean", "TemperatureMean", "GrayCx", "GrayCy", "Moment2x", "Moment2y", "Momentxy",
    "GrayMoment2x", "GrayMoment2y", "GrayMomentxy", "Anisometry", "Skewness", "Kurtosis", "Circularity", "Bulkiness",
    "StructureFactor"
  ]
```

```
]
  csv_column_types = [
    "string",    # Date Time
    "string",    # Elapsed Time
    "string",    # Frame Number
    "string",    # Area
    "string",    # Cx
    "string",    # Cy
    "string",    # X
    "string",    # Y
    "string",    # Width
    "string",    # Height
    "string",    # Perimeter
    "string",    # FormFactor
    "string",    # Orientation
    "string",    # Eccentricity
    "string",    # EulerNumber
    "string",    # HoleCount
    "string",    # TouchesBorder
    "string",    # FeretDiameter0
    "string",    # FeretDiameter90
    "string",    # Compactness
    "string",    # GrayMass
    "string",    # GrayMean
    "string",    # TemperatureMean
    "string",    # GrayCx
    "string",    # GrayCy
    "string",    # Moment2x
    "string",    # Moment2y
    "string",    # Momentxy
    "string",    # GrayMoment2x
    "string",    # GrayMoment2y
    "string",    # GrayMomentxy
    "string",    # Anisometry
    "string",    # Skewness
    "string",    # Kurtosis
    "string",    # Circularity
    "string",    # Bulkiness
    "string",    # StructureFactor
]


  csv_delimiter = ";"

  csv_timestamp_column = "Date Time"
  csv_timestamp_format = "2006-01-02 15:04:05.000"
  name_suffix = "_Blob"



[[processors.strings]]
  tagpass = ["path"]
  [[processors.strings.replace]]
    field = "path"
    old = "\\"
    new = "\\\\"



[[inputs.tail]]
  files = ["C:\\Users\\joribrek\\Documents\\Files to database\\pixel\\*.csv"]
  from_beginning = false
  character_encoding = "utf-8"
  data_format = "csv"
  csv_header_row_count = 1
  csv_column_names = ["Date Time", "Elapsed Time", "Frame Number", "X", "Y", "Min", "Max", "Mean", "MeanTemperature"]
  csv_column_types = ["string", "string", "float", "float", "float", "string", "string", "string", "string"]
  csv_delimiter = ";"
```



```
  csv_timestamp_column = "Date Time"
  csv_timestamp_format = "2006-01-02 15:04:05.000"
  name_suffix = "_pixel"

  [[processors.strings]]
    tagpass = ["path"]
    [[processors.strings.replace]]
      field = "path"
      old = "\\"
      new = "\\\\"


[[processors.regex]]
  namepass = ["*"]  # Match all measurements

  [[processors.regex.fields]]
    key = "*"       # Match all field keys
    pattern = "(,)"   # Match commas in numbers
    replacement = "."   # Replace with a dot

  [[processors.regex.fields]]
    key = "*"       # Match all field keys
    pattern = "N/A" # Match "N/A"
    replacement = "0" # Replace "N/A" with "0"


[[processors.converter]]
  [processors.converter.fields]
    float = [
      "Min", "Max", "Mean", "MeanTemperature", "Area", "Cx", "Cy", "X", "Y", "Width", "Height", "Perimeter", "FormFactor",
      "Orientation", "Eccentricity", "EulerNumber", "HoleCount", "TouchesBorder", "FeretDiameter0", "FeretDiameter90",
      "Compactness", "GrayMass", "GrayMean", "TemperatureMean", "GrayCx", "GrayCy", "Moment2x", "Moment2y", "Momentxy",
      "GrayMoment2x", "GrayMoment2y", "GrayMomentxy", "Anisometry", "Skewness", "Kurtosis", "Circularity", "Bulkiness",
      "StructureFactor"
    ]



[[inputs.influxdb_v2_listener]]

  service_address = ":8087"


[[inputs.s7comm]]
  server = "192.168.1.161"
  rack = 0
  slot = 2
  timeout = "250ms"

  [[inputs.s7comm.metric]]
    name = "S7300"
    fields = [
      { name = "MachineOn", address = "DB1.X0.0" },
      { name = "MachineHand", address = "DB1.X0.1" },
      { name = "MachineAuto", address = "DB1.X0.2" },
      { name = "SpindelTurning", address = "DB1.X0.3" },
      { name = "FeedActive", address = "DB1.X0.4" },
      { name = "LaserOn", address = "DB1.X0.5" },
      { name = "InductionOn", address = "DB1.X0.6" },
      { name = "StartPos_X1", address = "DB1.R2" },
      { name = "EndPos_X1", address = "DB1.R6" },
      { name = "OffsetX2ToX1", address = "DB1.R10" },
      { name = "ActPos_X1", address = "DB1.R14" },
      { name = "ActPos_Y1", address = "DB1.R18" },
      { name = "ActPos_Z1", address = "DB1.R22" },
      { name = "ActPos_X2", address = "DB1.R26" },
      { name = "ActPos_Y2", address = "DB1.R30" },
```

```
    { name = "ActPos_Y2", address = "DB1.R30" },
    { name = "ActPos_Z2", address = "DB1.R34" },
    { name = "CalcVertOffs_Nozzle", address = "DB1.R38" },
    { name = "CalcHorOffs_Nozzle", address = "DB1.R42" },
    { name = "RodDia", address = "DB1.R46" },
    { name = "ProductionOrder", address = "DB1.S50.20" },
    { name = "SalesOrder", address = "DB1.S88.20" },
    { name = "SalesOrderPos", address = "DB1.S126.20" },
    { name = "SerialNr", address = "DB1.S164.20" },
    { name = "TimeToEnd", address = "DB1.S202.12" },
    { name = "PercentDone", address = "DB1.R214" },
    { name = "ReceipNr", address = "DB1.W218" },
    { name = "ProtectGas_On", address = "DB1.X220.0" },
    { name = "CrossjetGas_On", address = "DB1.X220.1" },
    { name = "ProtectGasFlow_Setp", address = "DB1.R222" },
    { name = "ProtectGasFlow_Act", address = "DB1.R226" },
    { name = "CrossjetGasFlow_Setp", address = "DB1.R230" },
    { name = "CrossjetGasFlow_Act", address = "DB1.R234" },
    { name = "ExhaustTemp", address = "DB1.R238" },
    { name = "NozzleTemp", address = "DB1.R242" },
    { name = "ProtectGlasTemp", address = "DB1.R246" },
    { name = "PF_ModeSer", address = "DB1.X250.0" },
    { name = "PF_ModePar", address = "DB1.X250.1" },
    { name = "PF_Ready", address = "DB1.X250.2" },
    { name = "PF_Busy", address = "DB1.X250.3" },
    { name = "PF_CH1_Active", address = "DB1.X250.4" },
    { name = "PF_CH1_Starting", address = "DB1.X250.5" },
    { name = "PF_CH1_Stopping", address = "DB1.X250.6" },
    { name = "PF_CH1_Running", address = "DB1.X250.7" },
    { name = "PF_CH1_Warn", address = "DB1.X251.0" },
    { name = "PF_CH1_Err", address = "DB1.X251.1" },
    { name = "PF_CH1_ComOK", address = "DB1.X251.2" },
    { name = "PF_CH2_Active", address = "DB1.X251.3" },
    { name = "PF_CH2_Starting", address = "DB1.X251.4" },
    { name = "PF_CH2_Stopping", address = "DB1.X251.5" },
    { name = "PF_CH2_Running", address = "DB1.X251.6" },
    { name = "PF_CH2_Warn", address = "DB1.X251.7" },
    { name = "PF_CH2_Err", address = "DB1.X252.0" },
    { name = "PF_CH2_ComOK", address = "DB1.X252.1" },
    { name = "PF_CH1_DiskAct", address = "DB1.R254" },
    { name = "PF_CH1_StirrerAct", address = "DB1.R258" },
    { name = "PF_CH1_HopPresAct", address = "DB1.R262" },
    { name = "PF_CH2_DiskAct", address = "DB1.R266" },
    { name = "PF_CH2_StirrerAct", address = "DB1.R270" },
    { name = "PF_CH2_HopPresAct", address = "DB1.R274" },
    { name = "Ind_Frequenz", address = "DB1.R278" },
    { name = "Ind_Power", address = "DB1.R282" },
    { name = "Ind_Waterflow", address = "DB1.R286" },
    { name = "Ind_Watertemp", address = "DB1.R290" },
    { name = "Ind_TempSetp", address = "DB1.R294" },
    { name = "Ind_TempAct", address = "DB1.R298" },
    { name = "Ind_ErrID", address = "DB1.DW302" },
    { name = "La_PowerSetp", address = "DB1.R306" },
    { name = "La_TempSetp", address = "DB1.R310" },
    { name = "La_TempAct", address = "DB1.R314" },
    { name = "TimeLeft_Tube1_PFtoSwitch", address = "DB1.R318" },
    { name = "TimeLeft_Tube2_PFtoSwitch", address = "DB1.R322" },
    { name = "TimeLeft_Switch1", address = "DB1.R326" },
    { name = "TimeLeft_Switch2", address = "DB1.R330" },
    { name = "TimeLeft_Tube_SwitchToNozzle", address = "DB1.R334" },
    { name = "TimeLeft_Nozzle", address = "DB1.R338" },
    { name = "TimeLeft_PF_CH1", address = "DB1.R342" },
    { name = "TimeLeft_PF_CH2", address = "DB1.R346" },
    { name = "TimeLeft_Protectionglass", address = "DB1.R350" }
  ]



[[processors.converter]]
  [processors.converter.fields]
    tag = ["LaserOn", "InductionOn"]
```


The code displayed below is the code that is running on the Fraunhofer PC for the collection of the EMAqS, SensorMonitor and linescanner data and to send it to the Xiris PC

```
[agent]

  interval = "1500ms"

  round_interval = true

  metric_batch_size = 1050

  metric_buffer_limit = 60000

  collection_jitter = "0s"

  flush_interval = "3s"

  flush_jitter = "0s"

  precision = ""


[[outputs.influxdb_v2]]
  urls = ["http://192.168.1.223:8087"]
  organization = "Van Halteren Technologies - Boxtel"
  bucket = "CDOWAA"

[[inputs.internal]]
  collect_memstats = true
  collect_gostats = true

[[inputs.tail]]
  files = ["C:/Fraunhofer/SensorMonitor/*.csv"]
  from_beginning = false
  data_format = "csv"
  csv_header_row_count = 1
  csv_column_names = ["Time in ms", "Optiek beschem glas", "Nozzle", "Afzuiging", "R.W 1 H1 in", "R.W 2 H2 uit", "R.W 3 H2 in", "R.W 4 H1 uit", "Pyro. temp.", "Dust Monitor"]
  csv_column_types = [
    "string",  # Time in ms
    "string",  # Optiek beschem glas
    "string",  # Nozzle
    "string",  # Afzuiging
    "string",  # R.W 1 H1 in
    "string",  # R.W 2 H2 uit
    "string",  # R.W 3 H2 in
    "string",  # R.W 4 H1 uit
    "string",  # Pyro. temp.
    "string"  # Dust Monitor
  ]

  csv_delimiter = ";"
  csv_tag_columns = ["path"]

  csv_timestamp_column = "Time in ms"
  csv_timestamp_format = "unix_ms"
  name_suffix = "_Sensormonitor"



[[processors.strings]]
  namepass = ["tail_Sensormonitor"]
  [[processors.strings.replace]]
    tag = "path"
    old = "C:\\Fraunhofer\\SensorMonitor\\Thermoelemente_"
    new = ""
[[processors.strings]]
  namepass = ["tail_Sensormonitor"]
  [[processors.strings.replace]]
    tag = "path"
    old = ".csv"
    new = ""

[[processors.starlark]]
  namepass = ["tail_Sensormonitor"]
  source = '''
load("logging.star", "log")

def apply(metric):
  datetime_str = metric.tags["path"]
  parts = datetime_str.split("__")
  date_parts = parts[0].split("_")
  time_parts = parts[1].split("_")

  formatted_datetime = "{}-{}-{}T{}:{}:{}".format(date_parts[0], date_parts[1], date_parts[2], time_parts[0], time_parts[1], time_parts[2])
  metric.fields["formatted_path"] = formatted_datetime
  return metric
'''
[[processors.converter]]
  [processors.converter.tags]
    string = ["formatted_path"]



[[processors.timestamp]]
  field = "formatted_path"
  source_timestamp_format = "2006-01-02T15:04:05"
  source_timestamp_timezone = "Europe/Amsterdam"
  destination_timestamp_format = "unix_ms"
```

```
[[processors.starlark]]
  namepass = ["tail_Sensormonitor"]
  source = '''
load("time.star", "time")
load("logging.star", "log")

def apply(metric):
  original_timestamp_ns = metric.time  # Original timestamp in nanoseconds
  formatted_timestamp_ms = int(metric.fields["formatted_path"])  # Formatted timestamp in milliseconds

  new_timestamp_ns = original_timestamp_ns + (formatted_timestamp_ms * 1000000)  # Convert ms to ns and add

  metric.time = new_timestamp_ns
  return metric
'''


[[processors.timestamp]]
 namepass = ["tail_Sensormonitor"]
 field = "Time in ms"
 source_timestamp_format = "unix_ms"
 destination_timestamp_format = "2006-01-02 15:04:05.000"


fieldexclude = ["formatted_path"]



[[processors.regex]]
  namepass = ["*"]  # Match all measurements

  [[processors.regex.fields]]
    key = "*"       # Match all field keys
    pattern = "(,)"   # Match commas in numbers
    replacement = "."   # Replace with a dot

  [[processors.regex.fields]]
    key = "*"       # Match all field keys
    pattern = "N/A" # Match "N/A"
    replacement = "0" # Replace "N/A" with "0"


[[processors.converter]]
  [processors.converter.fields]
    float = ["Optiek beschem glas", "Nozzle", "Afzuiging", "R.W 1 H1 in", "R.W 2 H2 uit", "R.W 3 H2 in", "R.W 4 H1 uit", "Pyro. temp.", "Dust Monitor" ]



#[[aggregators.basicstats]]
#  period = "500s"
#  drop_original = false
#  fieldinclude = ["R.W 1 H1 in", "R.W 2 H2 uit", "R.W 3 H2 in", "R.W 4 H1 uit"]
#  stats = ["mean"]


#[[aggregators.derivative]]
#  period = "50s"
#  fieldinclude = ["R.W 1 H1 in_mean", "R.W 2 H2 uit_mean", "R.W 3 H2 in_mean", "R.W 4 H1 uit_mean"]
# suffix = "_derriv"
#  variable = "Time in ms"




[[inputs.tail]]
  files = ["C:\\Fraunhofer\\LompocPro\\Archiv\\*\\*.dat"]
  from_beginning = false
  data_format = "csv"
  csv_header_row_count = 10
  csv_delimiter = " "
  csv_column_names = ["time_ms", "EMAqS_temperature", "set_laser_power", "scanning_speed"]
  name_suffix = "_Processdat"
  path_tag = "path"
  csv_timestamp_column = "time_ms"
  csv_timestamp_format = "unix_ms"



[[processors.strings]]
  namepass = ["tail_Processdat"]
  [[processors.strings.replace]]
    tag = "path"
    old = "C:\\Fraunhofer\\LompocPro\\Archiv\\"
    new = ""
[[processors.strings]]
  namepass = ["tail_Processdat"]
  [[processors.strings.replace]]
    tag = "path"
    old = ".dat"
    new = ""

[[processors.starlark]]
  namepass = ["tail_Processdat"]
  source = '''
load("logging.star", "log")

def apply(metric):
  # Extract the date and time parts from the path tag
  datetime_str = metric.tags["path"]
  parts = datetime_str.split("_")


  folder = parts[1]
  year = parts[2]
  month = parts[3]
  day = parts[4]
  hour = parts[5].split("-")[0]
  minute = parts[5].split("-")[1]
  second = parts[5].split("-")[2]
```



```
  hour = parts[5].split("-")[0]
  minute = parts[5].split("-")[1]
  second = parts[5].split("-")[2]

  # Format the date and time
  formatted_datetime = "{}-{}-{}T{}:{}:{}".format(year, month, day, hour, minute, second)

  # Set the new fields
  metric.fields["folder"] = folder
  metric.fields["formatted_datetime"] = formatted_datetime

  return metric
'''
fieldexclude = ["folder"]



[[processors.converter]]
  [processors.converter.tags]
    string = ["formatted_datetime"]

[[processors.timestamp]]
  field = "formatted_datetime"
  source_timestamp_format = "2006-01-02T15:04:05"
  source_timestamp_timezone = "Europe/Amsterdam"
  destination_timestamp_format = "unix_ms"


[[processors.starlark]]
  namepass = ["tail_Processdat"]
  source = '''
load("time.star", "time")
load("logging.star", "log")

def apply(metric):
  original_timestamp_ns = metric.time  # Original timestamp in nanoseconds
  formatted_timestamp_ms = int(metric.fields["formatted_datetime"])  # Formatted timestamp in milliseconds

  new_timestamp_ns = original_timestamp_ns + (formatted_timestamp_ms * 1000000)  # Convert ms to ns and add

  metric.time = new_timestamp_ns
  return metric
'''



[[processors.timestamp]]
 namepass = ["tail_Processdat"]
 field = "Time in ms"
 source_timestamp_format = "unix_ms"
 source_timestamp_timezone = "UTC"
 destination_timestamp_timezone = "Europe/Amsterdam"
 destination_timestamp_format = "2006-01-02 15:04:05.000"

fieldexclude = ["formatted_path2"]



[[inputs.modbus]]
  ## Connection Configuration
  name = "modbus"  # Device name
  slave_id = 1        # Slave ID of the Modbus device
  timeout = "1s"      # Timeout for each request

  # TCP connection via Modbus/TCP
  controller = "tcp://192.168.210.5:502"

  ## Define the configuration schema
  configuration_type = "register"

  ## Register Configuration

  ## Analog Variables, Input Registers, and Holding Registers
  input_registers = [
    { name = "Laagdiktex", byte_order = "ABCD",   data_type = "UINT32",   scale=1.0, address = [0, 1]},
    { name = "Afstandx", byte_order = "AB",   data_type = "UINT16",   scale=1.0, address = [4]},
    { name = "Tempx", byte_order = "AB",   data_type = "UINT16",   scale=1.0, address = [5]},
  ]


[[processors.starlark]]
  namepass = ["modbus"]
  source = '''
def apply(metric):
      x = metric.fields['Tempx']
      y = 0.1 * x - 273.10
      metric.fields['Temp'] = y
      return metric
  '''
[[processors.starlark]]
  namepass = ["modbus"]
  source = '''
def apply(metric):
      x = metric.fields['Afstandx']
      y = (x - 32768)*0.005+250 #from scancontrol manual
      metric.fields['Afstand'] = y
      return metric
  '''
[[processors.starlark]]
  namepass = ["modbus"]
  source = '''
def apply(metric):
      x = metric.fields['Laagdiktex']
      y = x * 0.005
      metric.fields['laagdikte'] = y
      return metric
  '''

fieldexclude = ["laagdiktex", "Afstandx", "Tempx"]
tagexclude = ["host", "slave_id", "name","type"]
```

For any metric in every dashaboard a Flux query needs to be given to get the correct data from the database. Below are some examples of such queries.

A (influxdb_Boxappl)

```
from(bucket: "CDOWAA")
  |> range(start: v.timeRangeStart, stop: v.timeRangeStop)
  |> filter(fn: (r) => r["_measurement"] == "tail_Processdat")
  |> filter(fn: (r) => r["_field"] == "EMAqS_temperature")
  |> drop(columns: ["ProductionOrder", "LaserOn", "InductionOn", "SerialNr", "path" ])
  |> aggregateWindow(every: 500ms, fn: mean, createEmpty: false)
  |> yield(name: "mean")
```

Flux language syntax | Sample query | Help

B (influxdb_Boxappl)

```
from(bucket: "CDOWAA")
  |> range(start: v.timeRangeStart, stop: v.timeRangeStop)
  |> filter(fn: (r) => r["_measurement"] == "tail_HotCold")
  |> filter(fn: (r) => r["_field"] == "MeanTemperature")
  |> drop(columns: ["ProductionOrder", "LaserOn", "InductionOn", "SerialNr", "path"])
  |> aggregateWindow(every: 500ms, fn: mean, createEmpty: false)
  |> yield(name: "mean")
```

Flux language syntax | Sample query | Help

A (influxdb_Boxappl)

```
from(bucket: "CDOWAA")
  |> range(start: -5y)
  |> filter(fn: (r) => r["_measurement"] == "tail_Processdat" or r["_measurement"] == "S7300" or r["_measurement"] == "modbus" )
  |> filter(fn: (r) => r["_field"] == "EMAqS_temperature" or r["_field"] == "ActPos_X1" or r["_field"] == "laagdikte")
  |> filter(fn: (r) => r.ProductionOrder == "${Productionorder}" and r.SerialNr == "${SerialNr}")
  |> drop(columns: [ "InductionOn", "LaserOn", "SerialNr", "ProductionOrder", "path"])
  |> aggregateWindow(every: 5s, fn: mean, createEmpty: false)
  |> yield(name: "mean")
```

Flux language syntax | Sample query

```
let x = data.series[0].fields[1].values.map(value => value / 1000); // Convert x values to seconds
let y1 = data.series[0].fields[2].values;
let y2 = data.series[0].fields[3].values; // Assuming the second series is for the secondary y-axis plot
let trace1 = {
  x: x,
  y: y1,
  type: 'scatter',
  mode: 'markers',
  marker: { size: 2 },
  name: 'Temp.'
};
let trace2 = {
  x: x,
  y: y2,
  type: 'scatter',
  mode: 'markers',
  marker: { size: 2, color: 'red' }, // Customize the marker as needed
  yaxis: 'y2', // Link to the secondary y-axis
  name: 'laagdikte'
};
let layout = {
  xaxis: {
    type: 'linear',
    title: 'Kop positie (m)',
    gridcolor: 'grey',
    gridwidth: 1
  },
  yaxis: {
    type: 'linear',
    title: 'Temp °C',
    gridcolor: 'grey',
    gridwidth: 1
  },
  yaxis2: {
    type: 'linear',
    title: 'Laagdikte (mm)', // Label for the secondary y-axis
    overlaying: 'y', // Overlaying on the same x-axis
    side: 'right', // Position on the right side
    gridcolor: 'grey',
    gridwidth: 1
  }
};
```


To fill in the logbook and quality forms and input it into the database the following code was needed in grafana. This example shows the logbook code:

```
const payload = {};
// Construct the payload from the elements
elements.forEach((element) => {
  if (!element.value) {
    return;
  }
  payload[element.id] = element.value;
});
// Format the payload for InfluxDB line protocol
let influxPayload = '';
for (const key in payload) {
  if (influxPayload) {
    influxPayload += ',';
  }
  influxPayload += `${key}="${payload[key]}"`;
}
// Measurement name, tags, and fields
const measurement = 'logbook';
const tags = payload.ProductionOrder; // Add any tags if needed in the format 'tag_key=tag_value'
const fields = influxPayload;
const timestamp = Date.now() * 1e6; // Unix timestamp in nanoseconds
const influxLineProtocol = `${measurement},Productionorder=${tags} ${fields} ${timestamp}`;
return fetch("http://boxappl80.lp.lan:8086/api/v2/write?org=Van Halteren Technologies - Boxtel&bucket=CDOWAA&precision=ns", {
  method: 'POST',
  headers: {
    'Content-Type': 'text/plain',
    'Authorization': 'Token JLQIah[redacted]iw==', // Repla
    'Accept': 'application/json'
  },
  body: influxLineProtocol
}).then(response => {
  if (!response.ok) {
    throw new Error('Network response was not ok ' + response.statusText);
  }
  return response.text();
}).then(data => {
  console.log('Data successfully sent to InfluxDB:', data);
}).catch(error => {
  console.error('There was a problem with the fetch operation:', error);
});
```

Operator training and digital tools

As explained in the "two ways forward" section work was done on researching ways to improve operator training and information exchange. This will be added in this section as a future starting point for research and a source of ideas.

Currently there are a few sources of information for new and experienced operators to learn about the machine and learn how to operate it. These were studied and some things could be noted: It is no starting guide, there are not many pictures explaining it graphically and you have to have some prior knowledge but those prerequisites are given and specified.
There also is a logbook that has a place for remarks when something out of the ordinary happens, this is done on paper, so using this for a root cause analysis is harder because the data cannot be used in a program to correlate faults and settings. It would be helpful to digitize the reporting of this information and put this information in a database.

Existing tools:

SharePoint information system that guides users to forms and files the following can be found:
- Logbook
- Checklist rod production
- Form for iron measurement
- Work instructions

However, these resulting files have limited information, cannot be directly filled in and used
Easy to find documents but not use and interact with them

Interactive electronic technical manual: IETM

The idea of making static and text heavy manuals digital and interactive is one that already exist and there are a few companies that already make software and tools for this. This is usually referred to as IETM. This kind of manual can bring some added functionality. Mainly the addition to add 3D models, interactivity and select information based on the function of the one looking up the information (PE, OP, MA). So can we make sure the operator will only see relevant information while using the manual. Some companies that offer this kind of software are Adroitec, manual.to and codeandpixels. They add search options, hyperlinks, animations and easy access to explanation videos. However real interactivity or live documentation options are missing. It would help to evolve this kind of software to an interactive environment where the operator, process engineer and maintenance can make notes and report problems. This can include the state of parts, looking up recent problems per sub system and steps to take when certain incidents happen.

VR training / augmented reality

"The proposed training framework proved that Augmented Reality is a technology that can enhance training practices. Either for familiarization with Industry 4.0 systems or new assembly operations, augmented reality can lead to steeper learning curves and faster operator adaptation" [61]
Multiple papers have explored whether augmented reality can help factory and construction workers in training and inspection. It has promising results but I think It should add training abilities that are not possible in a conventional way (paper, signs and manuals)
Taqtile, seems to work efficiently and easy for this use-case.

Problem diagnosis

The fast and real-time diagnosing of problems is an important activity. If something in the process at VHT is not working as it is supposed to then that can result in wasted material, a wrongly coated rod or downtime of the machine. This makes this important to include in the tool that will be developed.

In a paper about a IETM centred maintenance system they talk about three types and levels of problem diagnosis[62]. These make a lot of sense and can be applied to the structure at VHT. The first is a 'simple diagnosis' made on experience and available knowledge of the machine. The faults that are found here are the most obvious malfunctions with clear causes. More complex faults and malfunctions are harder to detect and eventually diagnose, a look at some sensors, the state of the machine and the process is needed to see relations between things that happened. This is the second level the 'rapid diagnosis'. The third level is the most abstract level and needs data, sensor information, maintenance history, fault patterns and current conditions to be analysed an in this way the fault can be identified. The three parties OP, PE and MA will all have different abilities in performing one of the three types of diagnoses. The operator will make simple diagnoses and some rapid diagnoses. The process engineer will do mostly rapid and enhanced diagnosis. The maintenance people will come after the diagnosis is made to fix the problem. Some of the three types require their own information to make the reasoning. An idea of what is usually used and needed or not necessary needed in this reasoning can be found in Figure 69.

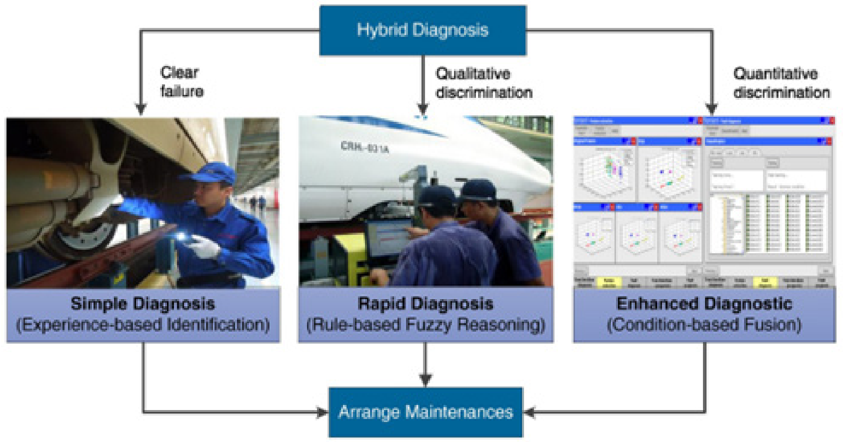


Figure 69 - Three levels of problem diagnosis [62]

	Experience-based	Rule-based	Condition-based
Failure history	limited	Required	Not required
Past operating conditions	helpful	Helpful	Helpful
Current Conditions	helpful	Required	Required
Identified fault patterns	Not used	Required	Required
Maintenance history	limited	Helpful	Helpful
Sensor data	used, with basic knowledge	used, with more knowledge	Needed, with analysis or calculations

Figure 28 - Diagnosis approaches (edited from[62])

Failure history

The logbook is part of the failure history, this can be digitized and classified in different categories. This can be displayed in the following two ways,
Occurrence, showing the categories of failures and the size of these categories gives the user an idea of the occurrence
Chronological list, Showing the list of faults chronologically with colours and tags defining what kind of fault it was.
For this data, a web app can be made using 'shiny'
Spatial/3D, A 3D model of the machine can be shown or overlaid on the real world and in this view, the parts causing the most failures are shown as a more red colour and parts that never cause issues more green.

Current Conditions

Different parts of the machine have different lifetimes and can have different states. This can be displayed by having a list of parts and components to which a value is coupled that says something about the state of that component. Like a value of how many hours it has been used during production like the tubes that only are okay for 75 hours of production to be safe or the state of wear of the nozzle that will be checked regularly and then get a value assigned to this result. The same idea can also be displayed in 3D where parts can be selected and then an overview with all the data of this part can be given.

Identified fault patterns

Identified faults from the past can be logged in an interactive fault tree that should therefore also be accessible but more importantly also expandable. In this way, the operator can work their way through the tree to find possible underlying faults. If it eventually appears to be a fault that is not in the tree it can be added for the next time something like this happens. Certain trends in sensor information can send an operator to a place in the tree where the possible causes can be found. This may help in the detection of problems. The step after is how to fix it independently.
Maintenance history
This can be an additional piece of information in the previously described list, 3D model or other system that represents the data.

Concluding from the research and the given problem statement we can conclude that to improve the interaction between the machine/operator and process engineer we can create a tool that tries to solve some bottlenecks and problems that the system faces.
This tool will be a combination of multiple solutions, combined into one system that will help the operator interact with the machine.

For van Halteren this tool will need to be built in an application that is easy to implement and maintain. Some options, that are discussed later are, Website/web app, Windows app, PDF's with links, Android app, VR/AR app and IETM software.

To help with this, a methodology can be made on how an information tool can be created for VHT that can teach new operators, be an accessible information tool, a tool that can be used for fault detection and a tool that documents faults and steps that need to be taken. Taking into account to not forget to state and explain why it should be done this way. This can be combined with a better interface, better displaying of sensor data and an overall more workable machine.

The knowledge and research on how to build this tool can be used to create a higher methodology for others who want to create these kinds of information and diagnostic tools.
Or on how to limit human errors in modern production? This method will tell why certain decisions are made in the design of the information tool and why those are important.

Requirements training manual part

The created training and information tool at VHT should be able to perform multiple functions. This will include training, documenting, fault reporting, information lookup, monitoring abilities and reaction plans.
At this moment the training manuals for the operators are limited. It is important for the operators to have a good basic understanding of the process. A visual based manual with all the workings and operations of the machine can help in creating this understanding.

For the learning aspect, the application/site that will be created, should be able to explain and visualize all the steps one has to do to use the LC machine. So that it can be used for new operators as an visual training tool. Also, the tool should always be accessible for experienced operators to lookup information and research possible faults. Not only should it be an training tool, it should also be a tool that can be used to document problems and solutions and buildup information over time. For this it will be important that the design leaves space for additional information and the content is editable by anyone. It should also give support in the decision making of the operator to increase the rate of correctly handled problems. The ability to add sensor data and have an overlay over them with information how to interpret them would also be helpful.
Bring all additional operations outside of touchscreen control to the same interface.

QR tool for inserting process parameters

Use an automatically generated QR code on the WPS or in the recipe to insert the important process parameters to the web page. In this way information on the web page could adjusted to the specific WPS specifications. This can help to show new operators on what to pay attention. It can for example show on a graph how much a certain temperature or feeding rate may differ.

Design of operator training tool

The layout and structure of the webpage will be an important aspect. It should be able to contain all possible information about the process, however it should still all be accessible in a quick way. This layout will determine the way information can be found for the operator/process engineer. To make it not overwhelming for the operators it would be helpful if the information can be filtered for the user. Some more in-depth information can for example be on 'expert/PE' pages and completely new operators can get an introduction page. To get a good overview of all the things there is to know about the process and operator actions and steps a mind map was made during research and exploring/testing of the machine.
Questions page
Elementor, divi
Security plug-in
Give information in same environment as needed, also for lookup > QR codes to website

Design of operator process check tool

The operators now have multiple screens, input screens of the sub-systems and computer screens with camera views. It would be helpful if this information is grouped and shown on the big monitor clearly, possibly with clear explanations and guidelines on how to interpret this data. In addition to this, the screen can house the interactive tools that can support them in their work.

These will be the following tools:
The interactive and expandable fault tree for problem diagnosis.
Interactive decision-and-reaction tool for operators
Digital repository of recent fault history to aid documentation and analysing capability.

Information transfer

At VHT the machines are operated by multiple operators in three shifts of 8 hours, this means that the machine can be running continuously. The changing of operators between these shifts makes it important that information about the state of the machine is transferred well to the crew that is taking over. Things that the first crew noticed have happened during operation can later in the process cause issues. So a short but helpful transfer of information can be built into the procedure at VHT.

Methodology to improve human-machine interaction

Reduce Human errors (training), exclude the possibility or give tools for detection.

The methodology described in this chapter is made to increase control, insight and fault detection in the interaction between the multiple stakeholders of an industrial machine and the machine itself. This method can then help companies to increase and streamline their production. There will be looked at the complete system as a whole. This can be the company's procedures, interactions between the stakeholders, information systems, operator training and automatization. This methodology has been created from what was learned during a case study at van Halteren Technologies. In this study, their laser cladding machine, interface, procedures and training resources were analysed with the goal of reducing production faults and increasing operator knowledge.

Because this research was done as a thesis at an external company the analysis was done with a fresh view of the problem and starting with limited knowledge of the machine. This means that a lot of the process first needs to be understood before helpful conclusions can be drawn. It can, however, also become a benefit for the work that has to be done. Because with this fresh view inefficiencies and unnecessary steps in processes can be identified. An added benefit is that the way in which the operation of the machine is learned can be used to come up with better training for future staff.

Training tool method

Be conscious of what you learn about the machine and write it down, this is apparently important information that needs to be in the information tool.

Mind map of all things that need to be learned

The complete and ordered information that is created in this way should then be displayed in a way that makes it possible to learn it efficiently and quickly.

For this it is important to know how people learn, (see those chapters),

In this section the methodology stated that describes how to make the eventual tool that will eventually help the three parties improve the operations. The way to make the tool can be described on the three levels; operator, Process engineer and maintenance.

Operator level

This method will the describe how one can find the information and what kind of information is important to put into the tool.
The human interaction and ergonomics concerned with the performance of the operator in a task oriented environment where the operator interacts with a system, machine and organisation play an big role in higher risk industrial production. Such as offshore oil and gas, aviation, marine and nuclear installations. This because the risks associated with human errors.[63] Although laser cladding is not high safety risk activity with big consequences if something goes wrong like stated in the list we can look at solutions found for these kinds of problems to possibly solve human errors in production. These errors can result in downtime, increased costs and missed deadlines.

A FTA was made to get an overview of possible failure points in the cladding process. As described in [64] a probability of occurrence can be coupled to the FTA. This can help to identify what is most likely to happen. However this is also something that happens in an FMEA.

FMEA can also be made to find an RPN , this can be used to classify the importance of what kind of knowledge the operator should have.

Human Reliability Analysis (HRA)

For work instructions there can be taken into account that for example in English instructions are written in simplified technical English and for other languages the equivalent. This makes sure that instructions are understandable even if it may not be the persons native language.