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Human Computer Interaction

Designing a visualization tool to aid operators in decision making for manual interventions on assembly-line based processes.

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Abstract

After the rise of industry 4.0, there have been major innovation to monitor the status of production processes amongst a plethora of industries. These innovations however, have mostly been aimed at monitoring processes and machines to convey their status, efficiency and technical problems, but failed to take into account the human element of decision making based on the information presented. Therefore, this research focuses on developing a visual aid to assist operators in the decision making process when executing manual interventions. A deeper understanding is gained on the information required by machine operators, their mental representations of expected information, and the type of decision making process that is applied. Using this newly acquired knowledge, several designs for a possible solution are brought forward, and their implementations benefits are discussed. We have found that a solid implementation can reduce stress in machine operators whilst also increasing their efficiency. Further possible advancements based on the opinions of machine operators, stakeholders and other experts are discussed, and can provide a solid basis for further research.

Contents

1 Introduction

In the processing and manufacturing industry, efficiency is a major performance indicator of a manufacturing plant. Many innovations to increase efficiency are developed to stay competitive in today's industry. One way to increase efficiency is to prevent breakdowns at machines within the assembly line, to reduce downtime. To accomplish this, a combination of scheduled maintenance and "fixing breakdowns as they happened" is still widely applied within the industry (Martin, 1994). The caveat of this strategy is that it can lead to over-maintaining introducing downtime where it wouldn't be necessary, or valuable time wasted diagnosing a breakdown as it happens. Although there have been substantial improvements in applying maintenance more effectively, using systems such as Maintenance Opportunity Planning (Chang et al., 2007), Random Preventive Maintenance, and crisis-related Reactive Maintenance (Jasiulewicz-Kaczmarek & Gola, 2019), there are still improvements to be made within the subspace of tool monitoring and planning of replacements and other manual interventions that are not classed as maintenance. As of the rise of Industry 4.0 (Lasi et al., 2014), also known as Smart Industry, a lot of multi-modal data can be extracted from machines to monitor the status of consumables, such as tools, current machine parameters, planned jobs, etc. Although systems have been developed to improve machine tools' performance and capability, such as an iPSS system for CNC by Zhu et al. (2011), or to monitor systems to show the current status of an assembly line, these systems seem to lack an intuitive way to convey necessary actions to a machine operator. Focusing on intervention and maintenance, these systems are not giving clear advice on what the best approach would be to fix a certain problem, as these methods are mainly focused on giving service solutions (Reményi & Staudacher, 2014) as opposed to instructions or advice. This does not only apply to consumable changes but also to other manual interventions (Jwo et al., 2021) that might be required within an assembly line. In literature, these manual interventions are also referred to as reactive maintenance (Wan et al., 2015).

The focus of this research is to aid machine operators in the decision-making process of when, how, and what type of manual intervention needs to be executed. Therefore, using an algorithm that takes into account a multitude of manufacturing domains, such as manufacturing tasks, manual tasks, machine data, resources, and materials (Zor et al., 2011), a system can be developed to extrapolate time windows in which predictable (consumable) interventions can be executed and recommend these to the user. It has been shown that recommendation systems can improve the quality of human-made decisions while reducing the search effort for information (Chen et al., 2013), while also reducing stress in machine operators and reducing machine downtime. These predicted interventions can then be acted upon by a machine operator when deemed necessary and/or fitting. We suspect that this will give the following advantages; A machine operator is better prepared as the system can show what kind of manual intervention is predicted and give the time window in which it best can be executed. A machine operator can select the best time to execute the manual intervention within the time window to uphold the efficiency of the assembly line. Required interventions and or maintenance on the same machine that are predicted in a similar period can be grouped into one, reducing machine stops.

To give clear advice to an operator, the output of this algorithm has to be visualized intuitively, providing data within the blink of an eye. For this reason, the scope is narrowed in order to develop a visualization tool to aid in planning reactive and predictive maintenance and interventions in the short-term future. To achieve this, decision-making is seen as a user task within the domain of information visualization, as optimal machine maintenance and use of consumables requires the expertise of a human operator, resulting in the fact that computational solutions may not result in the optimal efficiency (Dimara & Stasko, 2022; Sedlmair et al., 2012). This leads us to the following research questions:

"How to design a visual aid to assist operators in the decision-making process for the execution of manual interventions in assembly-line based processes?"

Based on the main research questions, the following sub-questions arise:

"What visualization strategies should be applied to create a high-level link between the different manufacturing domains, extracted expected interventions, and the operator?"

"How do operators encounter and deal with manual interventions in assembly-line-based manufacturing processes?"

"What information does an operator need to be well informed when executing manual interventions at assembly-line based machines?"

2 Literature Review

To find prior work done on this topic, a literature review was conducted, aimed at decision-making in visualizations, and visualization techniques for (multimodal) data in processing and manufacturing industries. From these related works, visualization techniques can be extrapolated to speed up our own design process.

2.1 Task abstraction

2.1.1 Visualization task identification

In order to understand what would be a good visualization technique, it is important to grasp what tasks the operator will conduct on the data. Pillat et al. (2005) provides us with a taxonomy of tasks related to multidimensional visualizations that can be divided into 2 categories, Visual Exploration or Analyzing and Intermediate or Support tasks. These tasks within these categories can later on be refined and applied to the domain of manufacturing.

Table 1

A taxonomy of users' tasks in visualizations

Visual Exploration / Analyzing	**Intermediate / Support**
Identify	Visualize
Determine	Configure
Compare	
Infer	
Locate / Lookup	

Note: Taken from Pillat et al. (2005)

The tasks that are most applicable to our system are given a short description below.

2.1.1.1 Identify This task corresponds to any action of finding, discovering or estimating based on the visual information. This task is regarded to be complete once the user has found the information he or she is looking for.

2.1.1.2 Determine This task refers to calculations, definitions or indications on the data. These could be statistical values, such as means and variances, but is also applicable to our scenario, as the task begins each time the user checks the data for a certain value and ends when a calculation is completed or the users goal is changed.

2.1.1.3 Compare This task refers to the user comparing different visual elements in the representation to allow him or her to make informed choices. This applies to our research in the sense that the operator might want to be able to compare manual intervention interval windows of different machines and make informed decisions on which intervention to address first.

2.1.1.4 Infer After identifying, determining, or comparing information, the operator should be able to infer knowledge on the intervention windows. The aim of this task is to give the user a better insight into his or her goal.

2.1.1.5 Locate / Lookup This task is related to finding specific data in the visual representation. For instance, all possible interventions are represented into a central timeline, but the operator would like to find the intervention window for one specific machine within the timeline. This task could be made easier using filters and or sorting, as described in the configure task.

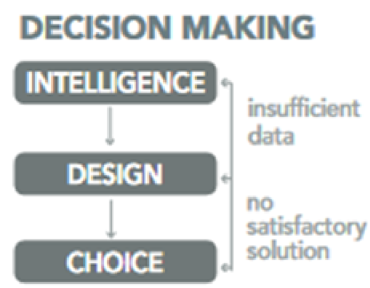
2.1.1.6 Configure Configuration is a support task to alter the output of the graphical representation of the system. This can contain but is not limited to altering visual representation by zooming or panning, dimensions, filters and. sorting. This task should be as intuitive as possible to optimize the efficiency of the system, minimizing the time an operator is playing around with the settings.

2.2 Visual aided decision making

Newell and Simon (1972) and Simon (1977) identify 3 main stages within the process of human decision making. These are intelligence, design, and choice. During the intelligence stage, the user will collect data relevant to the problem, or task, at hand. This stage can also be referred to as sensemaking, or data exploration (Dimara & Stasko, 2021; Keim et al., 2006; Weick et al., 2005). During the design phase, the user comes up with solutions to the problem or task at hand. This is where the to be designed tool could proof effective in aiding the user and have a large impact. During the choice phase, the user draws a conclusion from the solutions provided in the design phase, deciding what best fits the current context that the user is working in. Context could be modelled and considered when proposing possible solution, but as there are many human elements that are not predictable in the assembly industry, this would be an impossible task.

Figure 1

3 step decision making model by Herbert Simon (Newell & Simon, 1972; Simon, 1977)



Note: Taken from Dimara and Stasko (2021)

In order to provide sufficient data to the operator between the intelligence and the design phase, a thorough study needs has been conducted into the tasks that operators encounter, and how these tasks can be best visualized. In order to create a basis for this, the visualization strategies of similar systems that deal with data from assembly lines have been examined. (Padilla et al., 2018) provides a framework for decision making with visualizations across a multitude of disciplines. They present the definition for visualizations and decision making: "A visualization is an external visual representation that is systematically related to the information it represents, where the information it represents might be about objects, events, or more abstract information.” (Bertin, 1983; Hegarty, 2011; Stenning & Oberlander, 1995), where decision making is: “ A choice between two or more competing courses of action.” (Balleine, 2007). To design a good visualization for machine operators, we have to get a clear insight in their decision making process. Therefore, we need to determine the following; Are operators applying intuitive, low effort, autonomous decision making (Type I) or contemplative, effortful, informed decision making (Type II) (Kahneman, 2011)? Furthermore, do operators apply a top-down, or bottom-up encoding mechanism when trying to answer the conceptual question related to their task? And is this mechanism consistent between tasks and operators? According to (Pinker, 1990), the bottom-up approach guides the viewer through the following steps. First, the viewer creates a visual description, a mental encoding of the visual stimuli presented by the visualization. Next, the viewer tries to match the visual description to the most similar mental graph schema known. When this match is found, the visual description becomes instantiated, meaning a deeper understanding of the visualization is reached, allowing the viewer to answer the conceptual question using this instantiation of the graph. The top-down approach however, works in a reverse manner. The viewer first tries to construct a mental representation based on interrogation of the conceptual question, where is determined what information is necessary to reach a satisfactory answer. However, no matter the approach taken by the viewer, the outcome of the decision making process or response should be the same (Patterson et al., 2014). The approach does, however, impact visual encoding, pattern recognition, and working memory, as the top-down approach is more direct, aimed at answering the conceptual question, where the bottom-up approach gives the viewer a more global understanding of the visualization. Based on the task at hand, different approaches could be more efficient. To design a solid visualization for the decision making process a machine operator would experience, (Padilla et al., 2018) provides the following steps in their framework.

- Identify critical information needed for the users’ task.
- Determine which elements will attract the users attention.
- Create a visualization that aligns as close as possible to a users’ mental schema of the data.
- Reduce the number of cognitive transformation required for the decision-making process.
- Understand if the user is using Type I or Type II cognitive processing
- Evaluate the impact of individual differences such as graphic literacy and numeracy on visualization decision making.

2.2.1 Visualization task abstraction

To gain a better understanding of what kind of tasks the user is executing on our proposed tool, we need to zoom out from the domain specific task, and describe these task in a more abstract way. (Munzner, 2009) describes these abstract task as domain- and interface-agnostic operations performed by users. In order to disambiguate the means and end of our future users task, we will answer three questions that are central to the topology of abstract visualization tasks as proposed by (Brehmer & Munzner, 2013). These questions are: why is the task performed, how is the task performed, and what are the tasks inputs and outputs?. (Schulz et al., 2013) also applies this methodology, but expands upon it with questions in order to grasp the context and intentions of the user, using the following additional questions: Where in the data does the task operate?, When is a task performed?, and Who is executing a task?. By applying these questions, they are able to specify the target and the cardinality of data entities within the target, the order of tasks, if multiple, and the type of user. As who is unambiguous in the scope of this research, namely machine operators, we will not do a further analysis into differences among possible targeted user groups.

2.2.1.1 Why? To answers this question, we first need to determine the level of specificity of our users task is. These range from high-level (consume), mid-level (search), to low-level (query). Consumption is best described as a task in which the user needs to consume information in a domain context. This can be driven by a need to present information or to discover and analyze new information. Enjoyment is also placed at this level, but is out of scope for this research. In our case, we want present data for the user to consume and to guide them through a decision making process, as well as giving instructions. (Friel et al., 2001) Search tasks require the user to find or discover elements of interest into the visualization. As we want to make information as readily available to an operator as possible, we will assume that the location of the data is know to the user. However, the lookup tasks as described by (Andrienko & Andrienko, 2006; Pillat et al., 2005) still entails to pinpoint the element of interest in the visualization. Once the element(s) of interest has been located, the user can either identify, compare or summarize the information in these elements. Here, the use case of our system becomes more broad, as an operator might just want to know the next upcoming intervention (identify), or check which interventions can be executed at the same time, or at that require similar tools (compare). The operator could also just be looking at the visualized interventions at a whole, to see if there is enough available time to do other activities that are his or her responsibility, in which case they would summarize the data. In conclusion, a user of the proposed system would consume data, which the system presents in order to aid the decision making process. From all of this presented data, the user would lookup elements of interest in order to identify characteristics, such as intervention location, tools needed, time, etc., or to compare or summarize these characteristics over multiple tasks.

2.2.1.2 How? Now that it is clear what kind of tasks our users will perform with our visualization tool, we can focus on how we can facilitate these tasks, or configure our visualization (Pillat et al., 2005). Brehmer and Munzner (2013) has extracted multiple methods from several extant classification systems and has grouped them into three classes: encoding, manipulating, and introducing. Encoding is how data is represented as visual elements within our tool, and is to be designed to be as intuitive as possible for machine operators. Manipulation, or configuration allows operators to change the output of the visual representation, using techniques such as changing encodings, dimensions, output and others as described in 3.1.1. The class of introduction encompasses anything that has to do with the state of visual elements. Keywords in this group are, annotation, import, derive, and record. As per the temporal chronological nature of the data that is to be ingested by the system, introduction of new elements is rather straight forward, as they would just be appended to existing data. Introduction however, also describes the altering of existing data and/or elements by updating them with new information if conditions change or more data for a specific elements becomes available.

2.2.1.3 What? There is no clear answer as of what comprises a visualization according to Brehmer and

Munzner (2013). Their research showed that classification of "what", if present, ranged from entire datasets to precise specified data-attributes. However, a single absolute requirement is defined, which states that we must explicitly distinguish between the input and output of a task. Schulz et al. (2013) describes the "what" questions as characteristics of a visualization task: "What does a task seek?'. These characteristics are also referred to as features or patterns, that capture the aspects of data that the tasks wants to reveal. Schulz et al. splits these characteristics into two categories, low-level and high-level. Low-level refers to observing singular values of a particular object, while high-level focusses on more complex patterns and derivations from the given data, such as outliers, correlations, other statistical values, etc. These input and output, and therefore the characteristics of the data therefore depends heavily on the aim of the operator, as described in the last section of "Why?".

2.2.1.4 Where in the data? In order to determine the target of the users' task within the represented data, the following relations are defined:

- Temporal relation, which links the data objects to time intervals.
- Structural relation, which links multiple data objects to each other.

Given the suspected temporal nature of the visualization, as interventions are tied to time intervals, the target strongly depend on what knowledge the operator wants to extract from the visualization, as described in in "Why?" and "What?". The target can range from first data object on screen, to an analysis of the temporal spacing between elements. This same principle holds for the cardinality of the data, which is also explicitly stated in (Schulz et al., 2013). The target can consist of single instances for highlighting details, multiple instances for acquiring context, or all instances for getting a complete overview. However, it is beneficial to determine the target of highly recurrent tasks, and to guide the user to this target. If an operator is mainly concerned with the next upcoming intervention, and intermittently wants to achieve an overview, it can be advantageous to guide the user to the first element by default. However, this could clash if an intervention has priority, in which case the guiding aspect of the visualization should shift accordingly.

2.2.1.5 When? During preliminary stakeholder sessions, we determined that operators would use the visualization tool in an opportunistic way, as it is likely that the system will be deployed at monitors already present at machines. If an operator is operating a machine, he or she is already interacting with these displays. It is likely that this also carries over to other industries, as since the rise of industry 4.0, digitization is very prominent in all industries, including assembly processes (Ghobakhloo, 2020; Lu et al., 2020). Additionally, an expansion could be build upon the proposed system to allow for mobile notification when the start time of an intervention passes a set threshold. Visualizing all the data on a mobile device is not advisable as the screen space is rather limited for the amount of detail that operators need to execute an intervention. However, both of these additions are placed outside the scope of this research and referred to as possible further research.

2.3 Visualization strategies in similar systems

Now that a more clear idea is established on what task we can suspect the operators to execute on a visual aid, we can start to look at similar applications of multimodal visualizations in manufacturing settings. Zhou et al. (2018) gives a clear overview of visualizations used in an industrial setting for different phases of a manufacturing process (fig. 2). Studies that are of interest for this research are mainly located in the "Iron and Steel Industry" row and the "Visualization for Production Phase" column. Zhou continues to give a brief overview of all this research but a more in-depth look reveals relevant information regarding design choices for visualizations. Xu et al. (2017) proposed ViDX, a visual diagnostic tool aimed at assembly line performance in smart factories (fig. 3). Although this is more in-depth than the scope of this current research and mostly uses historical data where we would like to peak into the future, it still proposes interesting ideas. Just like in our research, Xu et al. designed a visualization tool focusing on a main assembly line that consists out of multiple workstations, and/or machines. Their approach of gathering data using Programmable Logic Controllers (PLC's) corresponds to our research, as each PLC can be seen as a node in the system, each providing its own data relative to that of the assembly line. This data is later used to populate a Marey's graph, which is expanded to show more historical fault data, label events with fault codes, and detect outliers in the system. The main takeaway from this paper is to use a temporal-based visualization to be able to show an operator what a machine did, is doing, and will be doing, and what can be expected in the future. Although we will mainly focus on the latter, historical data can be used to explain the system's choices, which can prove useful for diagnostics and analytics.

W. Wu et al. (2018) describes a visual analytic approach for equipment condition monitoring in smart factories in the process industry (fig. 4). Their aim is to build a visual analytics system with a semi-supervised framework to help managers and operators define health status of online equipment and derive meaningful rules or patterns for effective equipment condition monitoring In their report, they state that time series data is ubiquitous in smart factories, as most machines can send snapshots of their current status along with a timestamp. Based on this statement, they continue to argue that analyzing this time series-based data is a basic condition for monitoring the state of consumables and equipment in factories. A lot of research has been done on time-based visualization (Aigner et al., 2011), with the most prevalant methods graphing time on the X-axis. Within these approaches, changes of one or multiple attributes can be shown with respect to time (Harris, 1999; W. Wu et al., 2014). These approaches could form a solid basis for our first designs. Wu et al. contiues by listing a few design requirements that could be of great interest for our own design, suchs as "Interactive Feature Extraction", allowing operators to identify target sensors, and visualizing the extracted data, which the operater could correlate with their own expertise to gain trust in the system without having to understand the algorithms behind the feature extraction.

Sun et al. (2020) has developed a tool called PlanningVis, a dashboard developed to give a visual analytics approach to production planning in smart factories. Certain aspects of this research could be transferred to our own research and applied to the planning of manual interventions. Their dashboard visualizes the expected outcome of a production plan and how this compares to other plans, allowing a manufactures to select the most efficient way to produce a part. Sun et al. uses glyphs to show different plans and their differences, where the detailed production view is visualized in a linear fashion based on orders. Changing the input of this system to take in machine parameters and future executions, we should be able to create a similar system to show the impact of manual interventions, explaining when and why they should be executed in a certain time in-

Figure 2

A taxonomy of research for smart manufacturing applications

Industry Sectors \ Application Scenarios	Replacement Concept		Creation Concept			
	Equipment Internal Environment Visualization	Equipment External Environment Visualization	Visualization for Design Phase	Visualization for Production Phase	Visualization for Testing Phase	Visualization for Service Phase
Automotive Industry			(Kehrer et al. 2013) (Splechtna et al. 2015)	(Xu et al. 2017)	(Angeleli et al. 2011) (Matković et al. 2014) (Pajer et al. 2017)	(Alsallakh et al. 2017) (Chen et al. 2018) (Guo et al. 2018)
Energy Industry		(Höllt et al. 2011, 2013)	(Ivson et al. 2017)	(Arbesser et al. 2017) (Maljovec et al. 2016) (Zhou et al. 2017)		
Transportation Equipment Manufacturing	(Dutta et al. 2017, 2018)	(Takeshima et al. 2013) (Xue ei al. 2016)	(Kratz et al. 2014)			
Chemical Fibers Manufacturing			(Weissenbock et al. 2014)		(Amirkhanov et al. 2016) (Reh et al. 2012)	
Food Processing Industry				(Boukhelifa et al. 2013) (Sarkar et al. 2004)	(Chen et al. 2017)	(Chen et al. 2013)
Ordinaryly Machinery Manufacturing			(Peng et al. 2012)		(Amirkhanov et al. 2011, 2014)	
Iron and Steel Industry	(Zhou 2011)	(Wu 2001)				
Chemical Industry			(Beketayev et al. 2011)	(Wu et al. 2018)		
Specialized Equipment Manufacturing			(Coffey et al. 2013)			
Electronic Equipment Manufacturing				(Jo et al. 2014)		
Others		(Millette and McGuffin 2016)	(Wörner and Ertl 2011,2013)	(Post et al. 2017)		

Note: Taken from Zhou et al. (2018)

terval. Although this would require in-depth analyzing of planned jobs and all the possible outcomes based on machine configurations and when interventions are executed, this approach, or a similar one on a higher level, could considerably add to the trust in a system as an operator could see the expected impact of the choices to be made (Shin, 2021). More general visualization strategies for time oriented data are described by (Aigner et al., 2007), where they present a systematic view of possible visualizations. In addition to this, Aigner continues to cite Tufte (1988), who describes relations between time oriented data that can be applied in our tool, in order to convey relations of different interventions to the operator (fig. 5).

Sackett and Williams (2003) proposes a visual aid to support manufacturing and supervisory staff in manufacturing decision-making (fig. 6). Their main design objectives for this system are as follows:

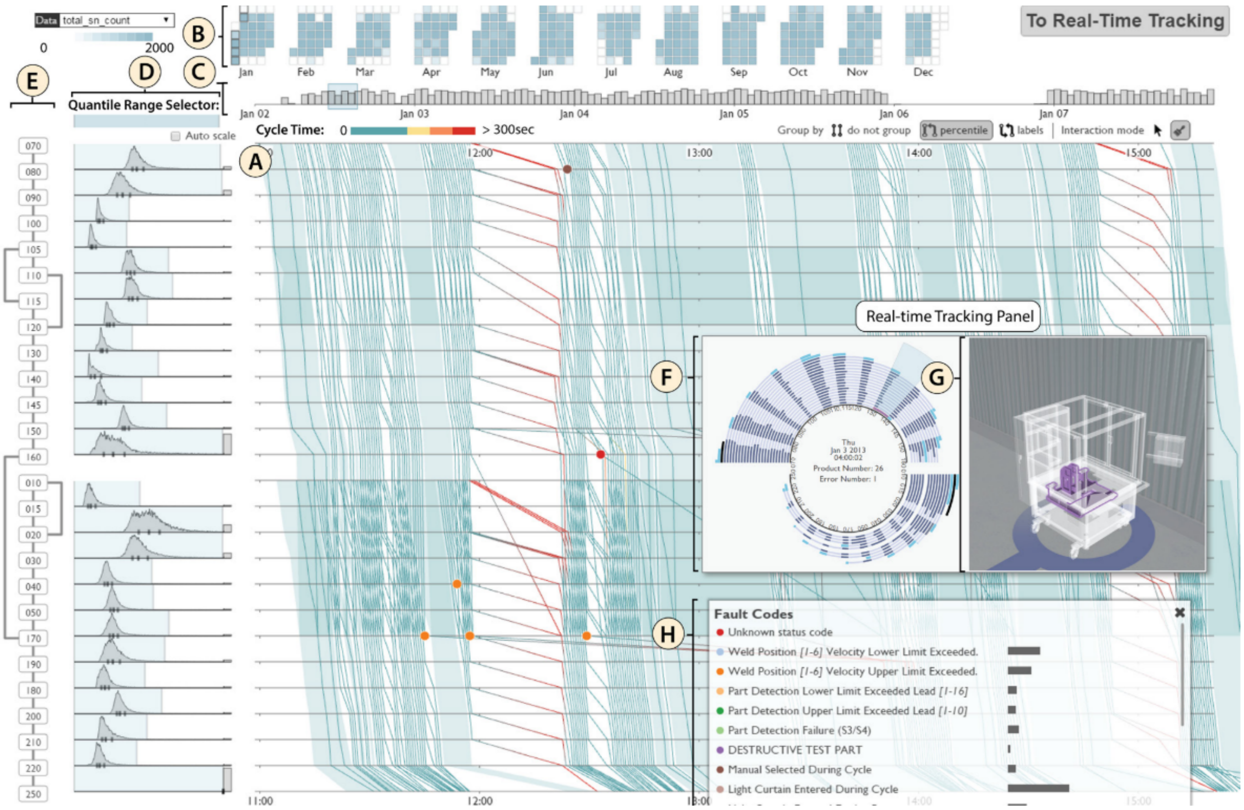
- Improved communication to the production line and management employees.
- Intuitive understanding of derivative production.
- Rapid and better quality decision-making.

Sackett & Williams continue to state the importance that the system should present information in a language-neutral format in order to cater to a wide audience of personnel. Furthermore, a good visual aid should provide broader access to information regarding a process in general. An informative visualization should provide intuitive insight, meaning less detailed knowledge and comprehension of the process in question are required in the first place, allowing for more cognitive load to be allocated to the decision-making process.

The visualization put forward as a solution by Sack-

Figure 3

ViDX: Visual Diagnostics of Assembly Line Performance in Smart Factories



Note: Taken from Xu et al. (2017)

ett and Williams (2003) contains three main elements, of which two are regarded as visual (fig. 6). First, a scatterplot, representing sequence performance. Second, gauges representing performance trends in different manufacturing areas. Sackett and Williams (2003) notes that using the visual information provided by the tool, its users were more confident in making decisions that impact the manufacturing process. Furthermore, there was strong agreement that the information provided, would allow for more fine-grained control in the manufacturing process and allow personnel to give better indications to the status of products in the assembly lines.

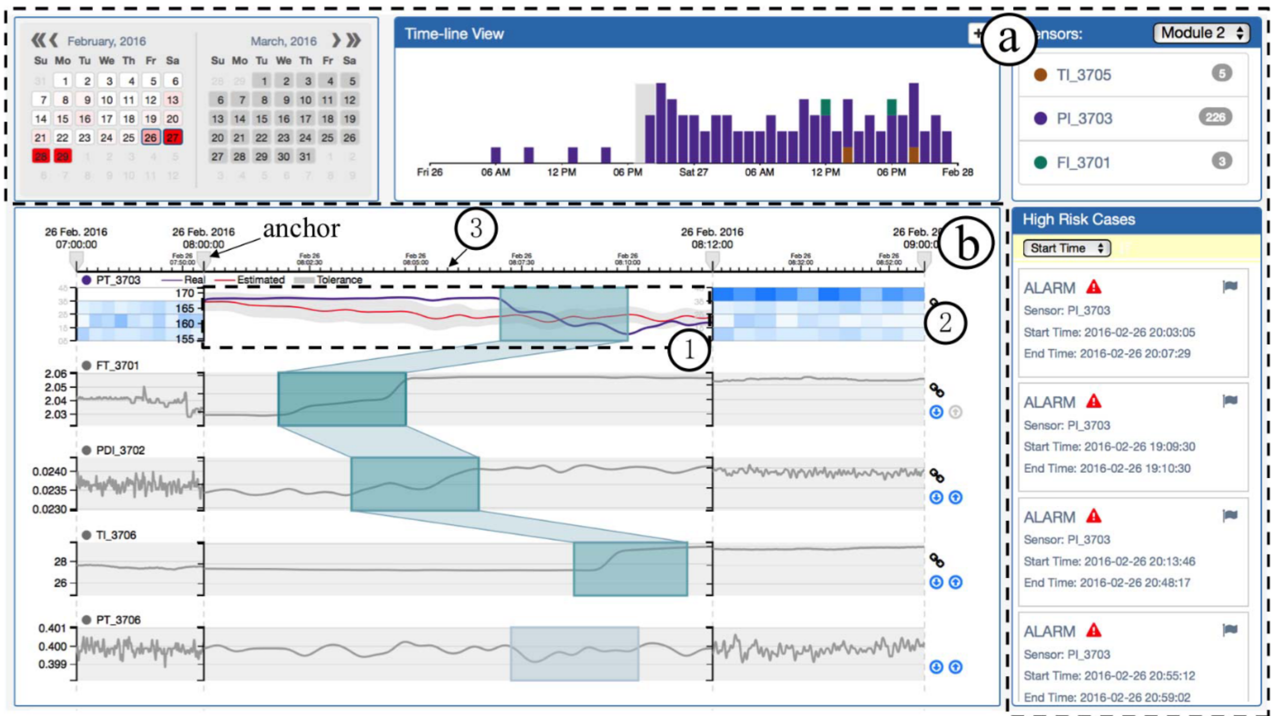
Aigner et al. (2007) also describes a visualization as presented by Aigner et al. (2005) called PlanningLines (fig. 7), a representation of time oriented data including temporal uncertainties. A representation that could very well suit our use case, as per its ability to indicate a possible start and end time of a manual intervention, as well as the possible predicted duration of an intervention, further increasing the knowledge in operators in order to aid their decision-making process.

2.3.1 The Manufacturing Domain

In order to create a good visual aid for the operators a solid understanding of different tasks within the manufacturing domain is required, as approaches can differ among these tasks Zor et al. (2011) denotes the follow-

Figure 4

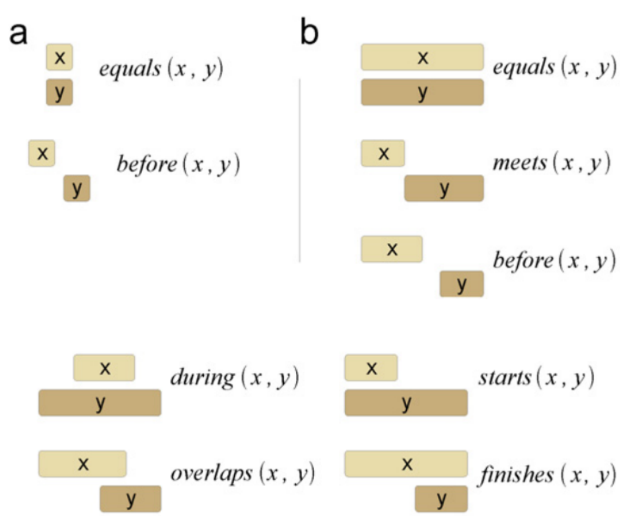
The system interface for detail inspection developed by Wu et al.



Note: Taken from W. Wu et al. (2018)

Figure 5

Temporal relations, between points (a) and intervals (b)



Note: Taken from Aigner et al. (2007)

ing elements and their manufacturing domain counterparts.

Table 2

Elements in the manufacturing domain

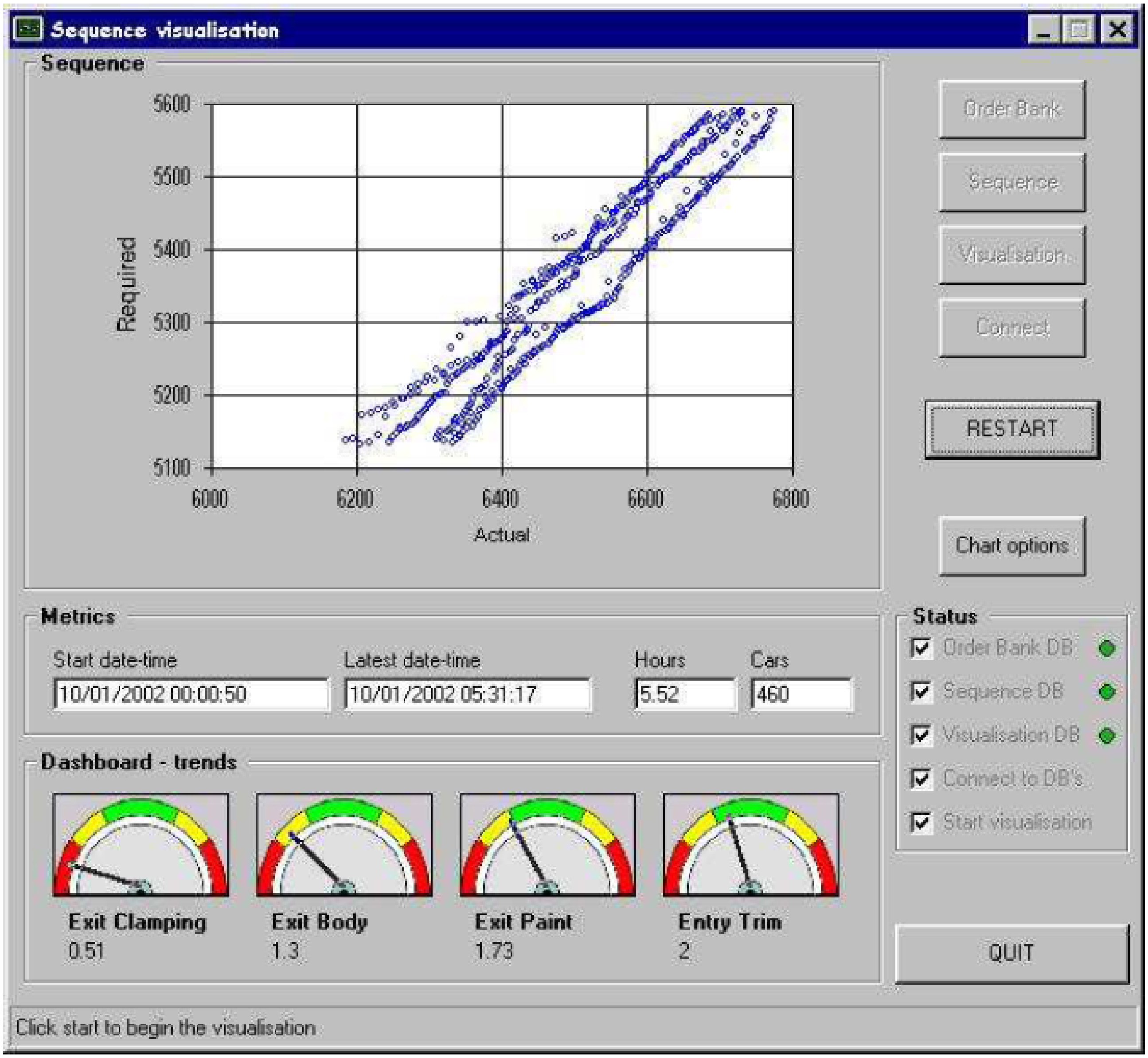
Element	Manufacturing Domain
Activity	(Manufacturing) Task
Human activity	Manual Task
Information	Operating Data, Machine Data
Material	Goods, Raw Material, Parts
Resource	Humans, Machines, Tools, Consumables

Note: Taken from Zor et al. (2011)

A manufacturing task is the (automated) execution of a preprogrammed job within the machine. Our research aims to ensure these tasks are executed smoothly by removing as many stops as possible or shortening the

Figure 6

Sequence visualization application user interface showing three component areas and multiple vehicle types in scatter plot.

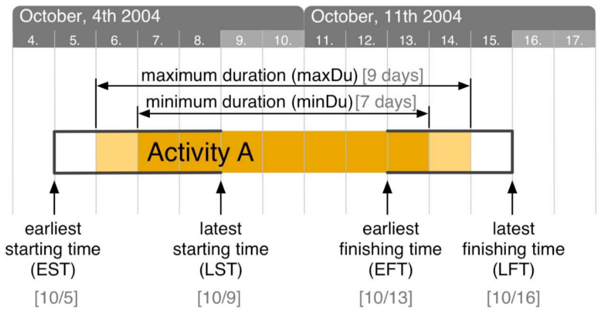


Note: Taken from Sackett and Williams (2003)

duration of these stops. An overview of current manufacturing tasks can be beneficial for an operator, but as there are already many of these systems in place, we will exclude this from the scope of our research. We want to focus on manual tasks, presenting as much information as possible to an operator about the requirements of a task before it needs to be executed, allowing for swift completion, and creating an intuitive dashboard to show information about these tasks to operators. Machine data, material and parts, machines, tools, and consumables will serve as the input of our system. Additional visualization of these parameters on their own

Figure 7

PlanningLines: Novel Glyphs for Representing Temporal Uncertainties and their Evaluation



Note: Taken from Aigner et al. (2005)

can add to the explainability of our system, arguing for the necessity and time placement of interventions. This data could also be extended further into the future to allow operators to make their own conclusion about a machine's needs, even though no manual intervention is (yet) predicted.

Sackett et al., (2006) provides a broad overview of data visualization opportunities in manufacturing, too many to list here, but a table overview is given in Appendix A. Based on the review of Sackett et al., (2006), we can conclude that, seen from table 2, there are many different elements of the manufacturing domain, each best represented by using different visualization strategies.(Sackett et al., 2006). Combining these into a coherent dashboard is expected to yield the best result in efficiency and usability for our system.

3 Method

To apply our research, a case study at Voortman Steel Group (VSG) is conducted. Voortman Steel Group is a leading manufacturer of steel parts and steel manufacturing machines. Using their knowledge, infrastructure and leading edge in assembly line automation, a solution to the proposed research questions can be designed and tested.

Within VSG, there are two main manufacturing departments using assembly lines on which this research can be applied. Voortman Steel Construction (VSC) focusses on creating steel parts for the construction industry using an automated assembly line. These parts consist out of fabricated steel beams, which have been cut to size, milled and/or drilled and marked for later manual assembly. Voortman Parts Manufacturing (VPM) focuses on creating steel parts out of plate material, using a bed cutting and milling process. As the research is most applicable to an assembly line setting, we focused on VSC, and for the sake of consistency, their current assembly line setup is used as an example for the remainder of this research. That being said, this research can easily be expanded to either different configurations and/or different sectors that use assembly line manufacturing.

3.1 VSC system description

The steel beam manufacturing line at VSC consists of a multitude of machines. First, beams are loaded on the in-feed buffer, after which they are fed onto the manufacturing line. The first step in the process is the blasting of the steel in order to clean and prepare it for further processing. Afterwards, the beams are fed into an inscriber. The inscriber can carve numbers or other marks into the beam to ease the manual assembly process on a construction site. The next step is drilling and/or milling. The beams are fed into a triple-axis drill where holes are created on the specified spots. Next, the line splits into two saws that will cut the processed beam up into individual parts. Afterwards, the line joins again to feed the parts through a plasma / oxyfuel cutter where any additional modification can be made if required, before reaching the out-feed buffer. A high-level overview of this process can be found in fig. 8.

3.2 Iterative Design

In order to come up with the best possible solution, an iterative design method is used. Using an iterative method with intermittent evaluations, problems within designs can be identified and mitigated, or even eliminated (Nielsen, 1993). First, a mock-up prototype has been developed, in order to gain footing in understanding the problem at hand and have a starting point for user requirement engineering. Next, the iterative design process will commence, in order to produce designs increasing in fidelity and to match our target groups' expectations.

3.3 User requirements

To get a solid basis for high-fidelity designs, a user requirement study has been conducted. Multiple methods were applied, such as stakeholder interviews, user focus groups, and design requirements from similar systems.

3.4 Evaluation

In order to evaluate if there is merit in our proposed solution, different tests have been conducted on the final design. As our time frame is limited, a full-scale implementation was not feasible, a demo case, however, was achievable. The demo presented a high-fidelity interface seeded with randomly generated simulated data. In this demo case, operators were asked to conduct a suite of tasks to test the usability of the system according to the System Usability Scale (Brooke, 2002) and to see if operators feel they would benefit from the system using a qualitative evaluation (Myers & Avison, 2002; Sackett & Williams, 2003). Lastly, expert opinions are acquired from a variety of internal and external sources, such as interviews and by proxy in literature.

3.5 Overall method overview

As we did not adhere to any conventional methodology, a small graphic has been created to gain a more solid understanding of the process (Figure 9). First, prototypes (Section 4) were created as a basis for user requirement engineering (Section 3). Based on these requirements, more designs were made, tested, and evaluated in an iterative design cycle (Section 7), before settling on a final design (Section 8). This final design has been evaluated more extensively and has been used to draw our main conclusions from (Section 9 & 10).

4 User Requirements

In addition to designing a good visual aid to assist operators in making well-informed intervention execution choices, we must also apply good interaction design, in order to ensure a high usability of the tool. In order to keep the design focused, a few software requirements were set up. As for identifying these requirements, different methods have been applied, such as extrapolating requirements from similar systems, stakeholder interviews and observational methods (Sedlmair et al., 2012), as well as feedback on initial designs.

Establishing good user requirements can be a difficult task, which is why we've chosen to apply the MoSCoW prioritization method for software requirement prioritization (MoSCoW for SRP or fuzzy MoSCoW)(Ahmad et al., 2018), allowing us to focus what is most important. Ahmad et al. expands on standard MoSCoW by defining functional requirements (FR), which describe the functionality of the software, and non-functional requirements (NFR), which describe how the system is

Figure 8

VSC Assembly line layout

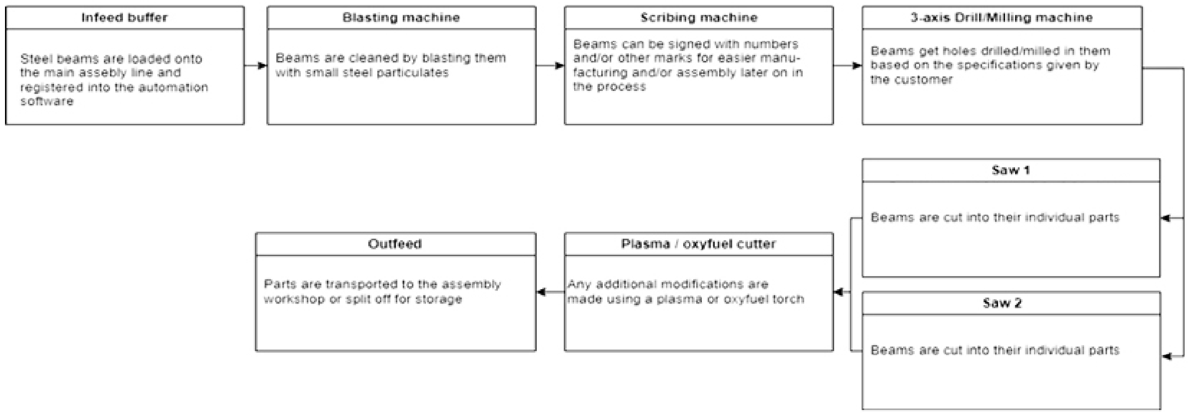
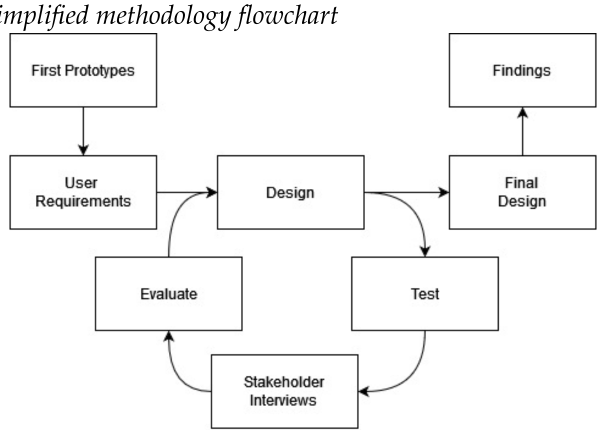


Figure 9

Simplified methodology flowchart



supposed to be, describing the quality of the system (Afreen et al., 2016). Although NFRs have received less attention than FRs within requirement engineering (Chung et al., 2012), they are significant as they deal with software quality (Mairiza & Zowghi, 2011). MoSCoW works with the following classifications:

- MH - Must have, this functionality must be included, even if it will cost more significant resources.
- SH - Should have, this functionality should be included, as it is expected by the user.
- CH - Could have, this functionality can benefit the user, and could be included if resources allow it.
- WH - Wont have, this functionality should not be integrated into the system.

As an in-depth look into the calculation is outside the scope of this research, only a small overview is given. Further details can be found in Appendix D.

Moscow for SRP applies the following method to calculate priorities for Design Requirements:

1. Apply a MoSCoW score to every FR and NFR
2. Convert the MoSCoW score to Triangular Fuzzy Numbers
3. Evaluate every FR against every NFR and calculate a combined prioritization score using the following formula (1):

$$\sum_{i=1}^{n} P_k = P(W_{FR_k} \otimes W_{NFR_i}) \quad (1)$$

Where P_k is the prioritization score of functional requirement k, evaluated over all non-functional requirements n, and W the Triangular Fuzzy Number respective to the MoSCoW score of the FR_k (table 3) or NFR_i (table 4).

Table 3

MoSCoW categories and TFN values for FR

MoSCoW	TFN
Must Have	(.66, 1, 1)
Should Have	(.33, .66, 1)
Could Have	(0, .33, .66)
Wont Have	(0, 0, .33)

Note: Taken from Ahmad et al. (2018)

Table 4

MoSCoW categories and TFN values for NFR

MoSCoW	TFN
Must Have	(5, 7.5, 1)
Should Have	(2.5, 5, 7.5)
Could Have	(2.5, 2.5, 5)
Wont Have	(7.5, 1, 1)

Note: Taken from Ahmad et al. (2018)

4.1 Functional Requirements

In this section, all Functional Requirements (FR) are listed, these requirements describe what the system should be able to do, and what interaction should be available to a user.

FR1: Visualization of temporal data.
The application is able to visualize temporal data in order to assist in the planning of interventions.

FR2: Show the current status of machines.
The application is able to show the current status of machines within the line.

FR3: Provide detailed information about an upcoming intervention.
In order to support the operator as well as possible, as much information should be provided on the upcoming intervention, allowing the operator to make well-informed decisions and prepare beforehand.

FR4: Allow for grouping of interventions within a similar time interval.
The application is able to group interventions on the same machine that are expected within a similar time frame in order to increase the efficiency of operators and reduce machine downtime.

FR5: Allow for adaptive opportunistic intervention planning.
If an operator is working at a machine, and there is another intervention that can already be executed but was originally planned for further into the future, the operator should be notified of this possibility.

FR6: Allow for filtering.
The application allows the user to filter on certain machines, events, and/or other variables to allow for quicker identification of the desired data.

FR7: Allow for zooming.
The application allows the user to zoom in on events, in order to increase the spatial resolution of the event, and allow for more data to be visible within the event.

FR8: Allow for navigation.
The application allows the user to navigate forward in time, allowing the user to discover elements that would otherwise not fit on the screen.

FR9: Allow for reordering of elements.
The application allows the user to reorder elements in the timeline graphic. As in a later design, all elements are combined in a singular timeline, this requirement will not be further evaluated.

4.2 Non-Functional Requirements

In this section, all Non-Functional Requirements (NFR) are listed, accompanied by a short description.

NFR1: The functioning of the system is intuitive.
The integrated functions in the system is easy to

use.

NFR2: The functioning of the system is precise and accurate.
Using a function should not deteriorate the precision of the system, values should not change, and a close-to real-world representation is kept.

NFR3: The functioning of the system has a quick response time.
The system should not induce any long loading times when processing a request from the user.

4.3 Prioritization Scores

In this section, the prioritization scores for all FRs are calculated.

Table 5

MoSCoW scores for FR in respect to NFR

NFR	FR	MoSCoW
NFR1	FR1	MH
	FR2	CH
	FR3	MH
	FR4	SH
	FR5	SH
	FR6	MH
	FR7	MH
	FR8	MH
NFR2	FR1	MH
	FR2	MH
	FR3	MH
	FR4	SH
	FR5	CH
	FR6	MH
	FR7	MH
	FR8	MH
NFR3	FR1	MH
	FR2	CH
	FR3	SH
	FR4	CH
	FR5	CH
	FR6	MH
	FR7	MH
	FR8	MH

Table 6

Importance weights for NFR

NFR	MoSCoW
NFR1	MH
NFR2	SH
NFR3	SH

Table 7

Prioritization scores for FR

FR	Score
FR1	15,093
FR6	15,093
FR7	15,093
FR8	15,093
FR3	13,685
FR4	8,928
FR2	8,346
FR5	7.270

4.4 Additional Secondary Requirements.

In this section, additional design requirements are discussed that, due to their nature, do not lend themselves to be evaluated using the MoSCoW for SRP method. Examples of these requirements are visual elements, such as additional cues, but also more general requirements that do not describe functionality within the system. Additional requirements that will arise during further phases of the design process will also be listed here.

ASR1: Implementation of some form of user authentication
Implement a (secure) method of identification in order for operators to access their personaly customized dashboard and manage their settings. While implementing this feature we have to keep in mind that due to the conditions in which the system is to be deployed, biometrics are not suitable, and physical access tokens are not desirable either, as these can get lost, break, or left at the terminal. As no sensitive data is to be stored on

the system, and there really is no incentive for a user to pretend to be a different operator, a simple 4-digit PIN should suffice.

ASR2: Include visual cues related to tasks (icons)
Including icons within bars in the timeline visualization will allow operators to quickly identify the nature of an intervention, without the need to look up additional details. These icons need to be checked for their explain -ability and need to be consistent in the entire system.

ASR3: Allow for feedback if an intervention was not executed within the predicted timeframe.
As discussed before, both stakeholders and a line manager were strongly opposed to "giving a performance score" to operators. However, both parties felt that some form of feedback could still be beneficial, but needs to be presented in such a way that the user will not feel he or she is being evaluated based on performance. One possible solution we came up with to mitigate this potential issue is to extend the predicted interval for an intervention past the suggested latest execution time to the point the intervention was actually executed. This way, there is still feedback to the user, and delayed intervention can be analyzed, but the inducement of negative emotions can be minimized or prevented. After further discussion based on design 1.1, we opted to not implement this feature from the beginning, rather than pointing it out as a possible solution may the need for this feedback arise. Based on feedback, it was also concluded that if this feature were to be implemented, it should be done in a different view from the main operator's home view, so as to not cloud the main purpose of the system, which is to aid in the planning of interventions. Adding more and more additional information to the graphic will complicate reaching this goal, which is something that should be avoided.

4.5 Implementation Requirements

In order to implement the proposed system, the following software implementation requirements (SIR) have to be met. These requirements are mostly related to being able to extract the necessary data to feed the system.

SIR1: Extract operations to be executed on materials.
To allow the system to extract expected interventions, it needs to be fed with the operations to be executed on materials that are currently on the assembly line. This data includes, but is not limited to:

- Material properties, such as height, thickness, length, and current rotation.
- What diameter and locations of holes to be drilled?
- The locations of saw cuts.
- The location of plasma cuts.
- All other machine operations.

SIR2: Extract operation lists of machines.
To make a more accurate prediction once a material has entered a machine, its automation list, containing all the operations by that machine, and possible tool changes, should be pushed to the system. This way, the accuracy of the time window of a predicted interval can be improved.

SIR3: Push machine states.
To expand upon the system and show an operator an overview of all the current statuses of machines in a singular overview, it could be beneficial to also push machine states to the system.

This, however, is not a requirement to predict interventions. Within VSC, this is currently done using the MQTT-protocol.

SIR4: Implement a database.
In order for the system to save and retrieve intervention information, a database is recommended. After some research, we recommend an Object-Oriented-Database, such as MongoDB. Using an OOD-schema, each interval can be a single entry, storing all necessary information about said interval.

5 Stakeholder Interviews

To have a clear idea of what manual interventions arise during an assembly process, or other processes that contain machines linked in a production line, stakeholder interviews were conducted with operators from different companies. The first few interviews were held at customers of Voortman, to limit ourselves to the steel manufacturing industry and to get a more in-depth look into the interventions used for our case study. Interviews at companies located in a different industry were conducted later on when a more polished initial design is available to see how the reported approach would transfer to other industries. The interviews were open-ended, allowing the operator to express their needs and flaws with the current system as they saw fit. We limited ourselves to 3 main questions, and a few conversation-steering questions if an interview drifted too far off-topic. These interview questions can be found in Appendix B.

5.1 Encountering Interventions

All operators were conformable about how they noticed when an intervention is necessary. Atop of the machines produced by Voortman is a light pole that can be in a few states, where the most applicable to our case is blue, which means the machine is in need of an operator. Other cases can be green, meaning that the machine runs automatically, flashing green, ready for start, yellow for a safety interruption and red for the machine being down.

Depending of the context in which operators work, if they have other task or responsibilities, the operator was not always directly aware of the state of these light poles. An operator that only tends to machines is more focused on the state of all the machines, as opposed to an operator that also has logistical tasks such as loading or unloading material. Furthermore, depending on the layout of the production line and other responsibilities, the whereabouts of an operator can differ significantly when a machine needs intervention. These whereabouts can either be at other machines the operator is tending to, which impact is greater if a large production line is deployed, or other locations in the production facility dependent of the operators' responsibilities.

As for most companies where operators where interviewed, there is some form of segregated responsibility for machines where one operator will tend to machines in the first section of the line, and a second operator to the last section. However, both operators will execute intervention on all machines if they notice a machine is not tended to quickly enough, independently on why the operator that should be responsible for that machine is not acting upon the intervention. This segregation is not present when a company only has a few machines confined in a small space, where a single operator is always close the control panel.

5.2 The nature of interventions

Operators, depended on the type of machine they are stationed at, reported a wide variety of possible interventions that need to be executed. These can vary from the cleaning of material or debris to consumable changes, whether because a different tool is needed or the tool has reached the end of its lifetime and needs to be replaced, to the alignment of material on belts, to ensure machines work accurately. Overall, consumable changes were the most prominent, while also being the type of intervention that is the most predictable. However, the nature of the consumable change can have a significant impact on the prediction, as there is no conclusive way to determine the end of life of a consumable without an element of human inspection. Operators noted that based on the kind of material, for e.g., its hardness, and thickness of the material has a great deal of impact on a tool's lifecycle. Our system would have to take all these factors into account in order to accurately predict when a tool's lifecycle is actually over. The current solution to this issue is that a machine will simply keep track of how many operations a tool has executed and notifies the operator when a certain threshold is crossed. An operator, if he deems that the tool can still be used, can override this, but has to do so every successive operation that uses the tool.

Dependent of the context of the operator and the state of the production line, (e.g. material is present in buffer zones between machines), opinions varied about the impact of interventions on the production process, as not every piece of material has the same processing time. This suggests that the location of the intervention and the state of the production line does have to be considered in order to prioritize certain interventions over others. As a rule of thumb, operators mentioned that they would first tend to machines where the outfeed buffer, the location where the materials processed by that machine go, is mostly empty. This is to ensure that any machines doing further operations on the same pieces of material will not also stop because of the preceding machine being stopped. Therefore, taking priority of interventions into account when designing our visualization has become a crucial factor that is still missing in preliminary designs.

5.3 Dealing with interventions

When an operator is executing an intervention, varied materials can be required. These can range from consumables themselves, to a variety of tools needed to interchange consumables or clean materials. Operators felt that providing details could streamline the intervention process, especially for newer operators with little experience. As mentioned before, different machines can have different priorities regarding their interventions. This also applies when interventions share the same or overlapping time windows. Also, as mentioned in section 5.1, operators have some unwritten rules of who is responsible for what. As these differ from operator to operator, we can not model all their possible rules, to assign tasks automatically. For all operators that had different responsibilities in addition to tending to machines, interventions had a higher priority over their other tasks and were executed as soon as feasible.

6 First Prototypes

In order to get a conversation flowing about design requirements and to get a better understanding on what is desired by the stakeholders, some Lo-Fi prototypes were created. These designs include some basic navigational functionality, but are not using any data. The main focus of these designs are layout, representation and functionality.

6.1 Prototypes

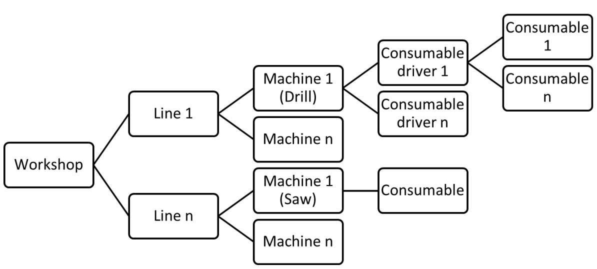
In this section, design choices for the first prototypes are discussed. Afterwards, the prototype are evaluated to see what changes are desirable.

6.1.1 Layout

For the first design, a top-down approach was chosen with modularity in mind. This means that a line operator could have a central location within a workshop, e.g., a factory that has multiple assembly lines, and can have a complete overview, selecting lines, machines and machine specific consumables. Due to the large variety of the machines, the last few layers can differ across the machines selected. A drill for instance will have multiple consumable drivers, in this case local storages, in which a multitude of drills can be present. A saw, on the other hand, will just have a single consumable.

Figure 10

Prototype 1 layout



6.1.2 Visualization strategies

As this is just a first prototype, very basic visualization strategies where implemented. For the expected interventions, a compounded timeline is displayed with marks on places where an intervention is to be expected. Hovering over one of these markers would show basic information regarding the intervention. Lines, machines and consumable drivers are annotated with an exclamation mark if they required immediate or rather soon attention from an operator. Selecting a line or machine would update the timeline to only show expected interventions specific to the current selection. Diving deeper into the system by selecting, for instance a consumable driver, a detailed overview can be viewed of the current status of the selected object.

Figure 11

Workshop overview containing production lines

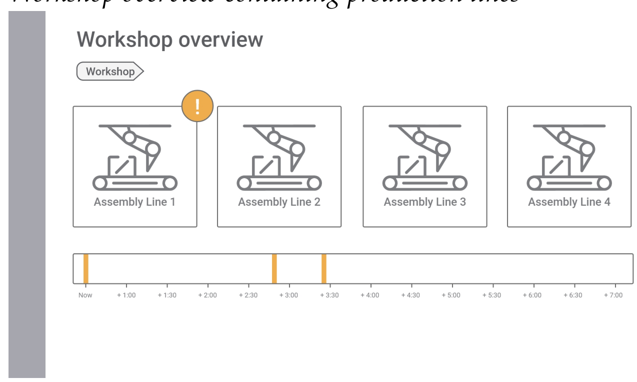
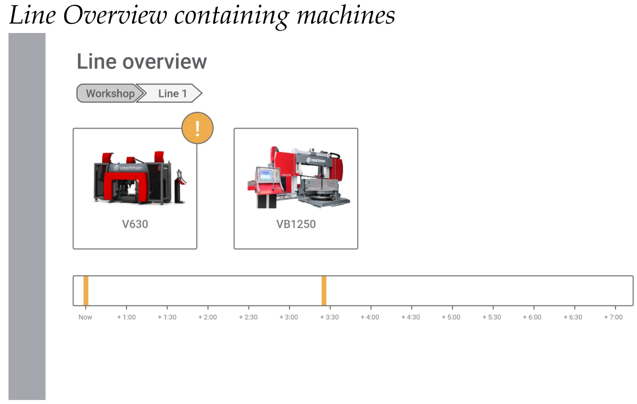


Figure 12

Line Overview containing machines



A great deal of useful feedback was received of the first preliminary design. These will be discussed in further detail in the design requirements, but a global overview is given here as they form the basis for the

Figure 13

Machine Overview

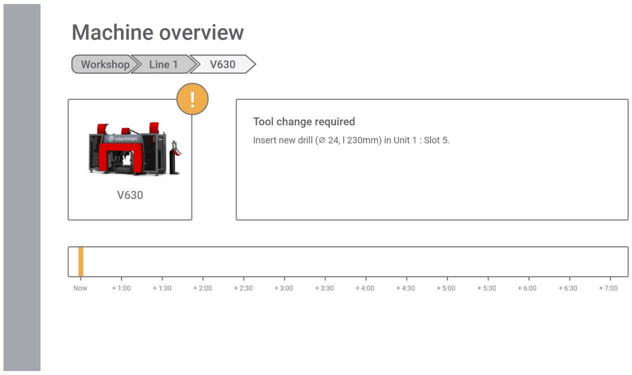


Figure 14

Consumable driver overview (3 Drill units) for a machine.

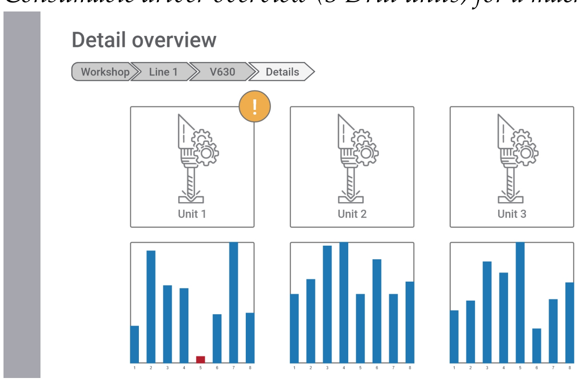
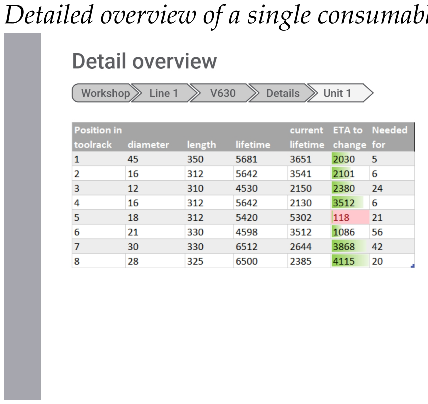


Figure 15

Detailed overview of a single consumable driver.



Position in toolrack	diameter	length	lifetime	current lifetime	ETA to change	Needed for
1	45	350	5681	3651	2030	5
2	16	312	5642	3541	2101	6
3	12	310	4530	2150	2380	24
4	16	312	5642	2130	3512	6
5	18	312	5420	5302	118	21
6	21	330	4598	3512	1086	56
7	30	330	6512	2644	3868	42
8	28	325	6500	2385	4115	20

second Lo-Fi prototype. The feedback below was given by supervisors and other stakeholders, such as software engineers.

- The layout can be changed to exclude the workshop overview as an operator is typically only assigned to a single line, reducing the amount of information that needs to be ingested by the user, improving the clarity of the dashboard.
- In addition to the compounded time line showing all interventions, machine specific timelines should be readily available.
- The current design lacks time windows, and what to do in case of an overlap.
- Instructions and/or advice should be more readily available to the operator, decreasing the number of actions an operator needs to execute in order to access this information.
- An operator should be able to have a more personal overview, only showing interventions that are relevant to the user. A subscription-based method could be applied to facilitate this.

6.2 Second prototype

Based on the first prototype and its accompanied feedback, a second prototype was created. This prototype will have more distinguished features, a better overview, and provides more detailed information.

6.2.1 Layout

Different system views have been moved to a side menu that will always be accessible for easy navigation. In this menu, an operator can navigate to the following screens;

- Operator Home (User specific system overview)
- Line Overview (Complete system overview)
- Machines (Machine overview and states)
- Assigned tasks (See all assigned tasks and manage

subscriptions to specific machines)

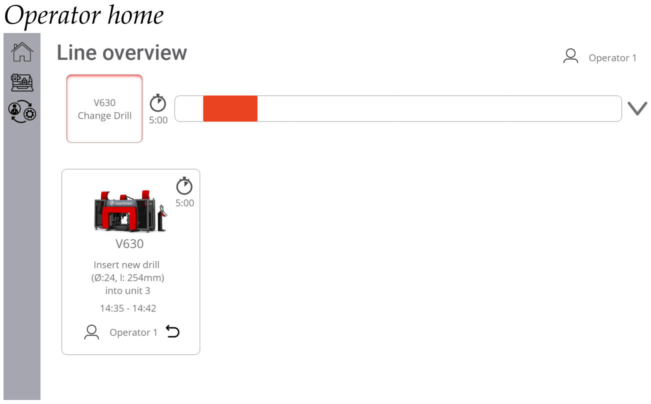
As a workshop rarely consists of more than one assembly line, the workshop overview was omitted, and the entry point of the visualization dashboard was changed to a user-specific line overview, annotated as "Home". In this overview, the operator will see a visualization specific to him/her. (fig. 16)

6.2.2 Visualization strategies

As the main focus was put on the general layout and functionality regarding the feedback of the previous prototype, the visualization strategy hasn't evolved, with the exception of the implementation of a card system.

Figure 16

Operator home



In the line overview (fig. 17, fig. 18), an operator can see all tasks, regardless of being assigned to the currently identified user. In addition to this, a card system was implemented to give more detailed information regarding upcoming interventions. These cards are in chronological order of expected interventions as seen in the compounded timeline. Furthermore, these cards will allow operators to assign the listed task to themselves (checkmark), release it back into the pool of unassigned tasks (return symbol), or see to whom the task was assigned. The task can also be discarded if deemed unnecessary (X). The compounded timeline can also be expanded to view a timeline per machine in the assembly line, allowing for an easy overview of what has to be done, at what time, and at which machine.

Figure 17

Line overview

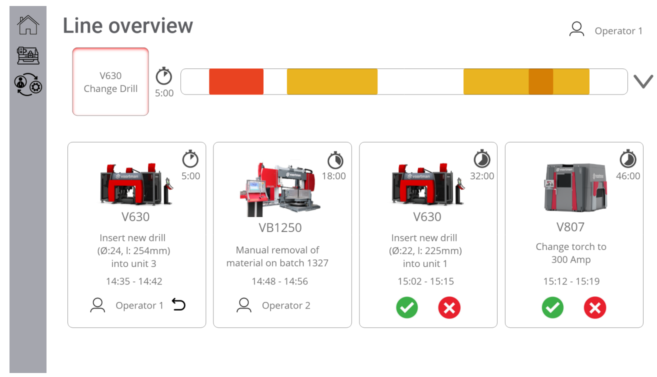
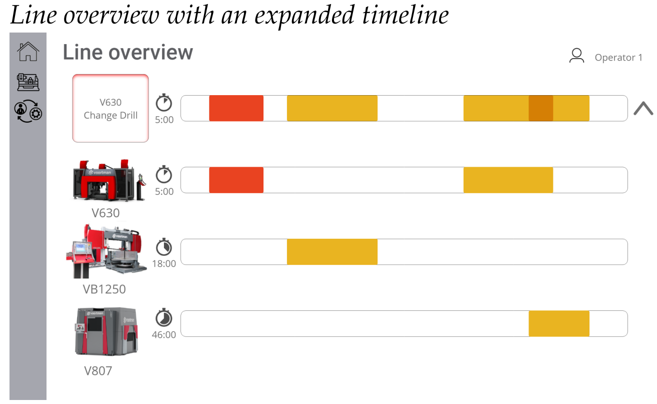


Figure 18

Line overview with an expanded timeline



In the machine view (fig. 19, fig. 20), an overview is given of all machines in the assembly line, their current states, events at the machine, and other useful information that might aid the operator in making a maintenance or intervention decision. A score representing intervention efficiency can also be displayed based on the number of interventions completed before their prospected deadline.

In the task allocation view (fig. 21), an operator can

Figure 19

Machine overview

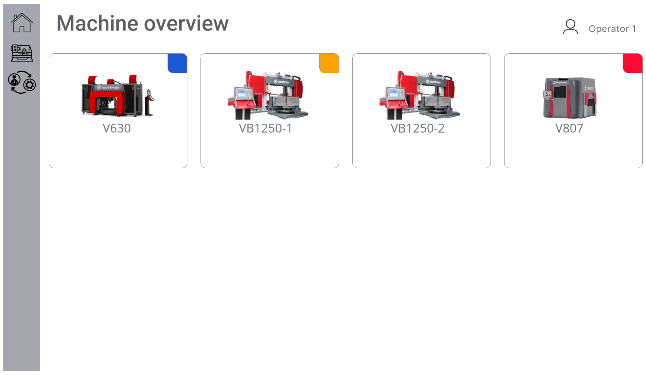


Figure 20

Machine Overview for the VB1250-1

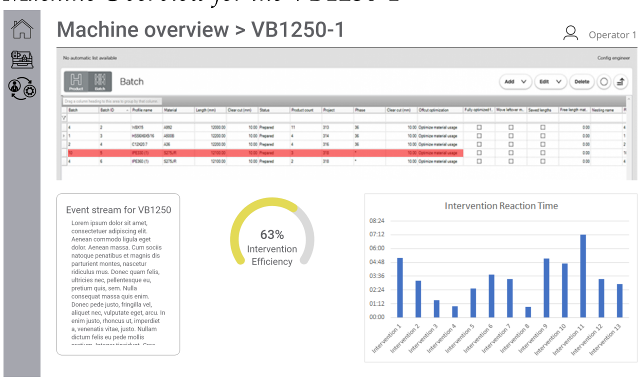
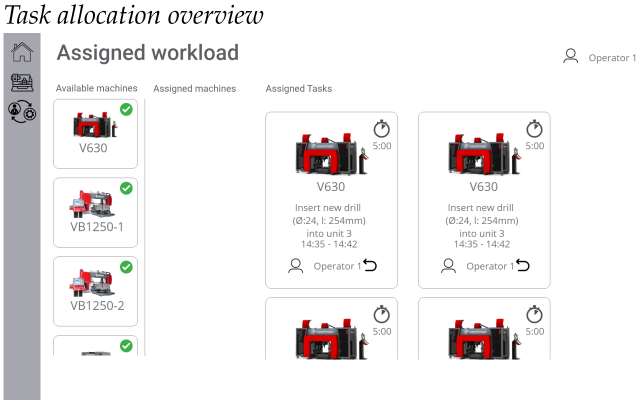


Figure 21

Task allocation overview



view all the tasks that are automatically or manually assigned to him/her. From here, the operator also has control over the current subscription, by either adding/removing subscriptions.

6.2.3 Feedback on the design

The current prototype conveys a clearer message, however, as there is more information on the screen, there is also more room for misinterpretation. The card system also created some confusion among stakeholders as the order of the cards (Figure 8) is not inherently clear. A possible solution to this problem would be to detach the timeline and the task cards more, in order to enforce the idea that these are 2 different visualization methods. However, there is merit in linking the 2 approaches together for easy identification of order and prospected time interval. Assigned task and subscription management should be moved into different views to declutter and reduce information overload. Assigned tasks could even be omitted as an overview of these tasks can already be found on the operator's home screen.

The intervention efficiency indicator is something the stakeholder were strongly opposed to, as they believe this sends the wrong signal to operators. Even if it is just an indicator aimed at aiding the operator, this could induce negative emotional responses in the operator (Groen et al., 2017). However, they do believe that some form of feedback based on the timely execution could be useful, this should not be portrayed as a performance indicator.

Furthermore, stakeholders felt that the prototype was already too established, and therefore might prevent interviewees from giving critique/feedback on overall looks and functionality. To mitigate this, a wireframe version of the second prototype was developed, before conducting interviews with machine operators. As the basic idea behind the wireframe and the second prototype is the same, no detailed description is given. An overview of the wireframe can be found in Appendix C.

6.2.4 Feedback from machine operators.

After a feedback session with the stakeholders, a secondary session was conducted with operators working at the main assembly line at VSC. First, the wireframe was shown in order to be more open to design critique. Operators noted that they wanted as little information presented to them as possible, in order to give some sense of calmness and control, while still being able to identify the details of upcoming interventions. This concept of preventing information overload and the accompanying emotional response is backed by Edmunds and Morris (2000), suggesting that we should only show information to the user that he or she specifically needs to do a certain task. A step towards this goal could be the removal of all the tasks cards that are assigned to different operators than the current user, as these tasks are no longer of interest to the current user, but do give a sense of stress, as these tasks are presented in the same way as jobs the current user would have to do.

Furthermore, an argument was brought forward about the chronological nature of the task cards, agreeing with other stakeholders that these should be more detached from the main timeline, where the timeline feature should only be used to gain a quick understanding of when an intervention is expected to happen, while the cards provide additional details. Operators would also like to see a feature where you can sort through the cards, having the ability to look ahead, while keeping the first upcoming intervention in view.

Feedback was also required from the assembly line manager about the "Intervention performance indicator" (which was omitted from the wireframe drawings), to see if there was any desire of checking up on his operators and their performance. The assembly line manager also strongly concurred with other stakeholders that presenting operators with a performance score might induce an unwanted emotional response. He also agreed that it could be beneficial in order to assist operators in planning future interventions more efficiently, but should not be presented in such a way that an operator would feel that he or she is being monitored.

7 Further Designs

In this section, the first designs based on the user requirements will be brought forth. Iterations between these designs will be slower as they will be more detailed. For each design we will discuss every applied user requirement, and how these have evolved from previous designs if applicable. As for the creation of the following designs, we have moved away from prototyping tools such as Adobe XD and Balsamiq and opted for web-based programming, as this method does allow for rather quick design iteration with more in-depth functionality, while also being able to ingest data. To facilitate this, a Node.JS framework was created using the ExpressJS framework (Express - Node.Js Web Application Framework, n.d.). Express was used create an API-based web application with multiple endpoints, enabling us to serve data to a user interface. For visualization elements, D3js was used, both for ease of use (both Express and D3 are written in JavaScript), the large amount of documentation available and its customizability (D3.Js - Data-Driven Documents, n.d.). Any images that are present in the designs are either sourced by Voortman Steel Group (pictures of machines, icons etc.), are free of copyright (icons) or are procedurally generated by an AI (avatars, this-person-does-not-exist.com (This Person Does Not Exist - Random Face Generator, n.d.))

7.1 Design 1.1

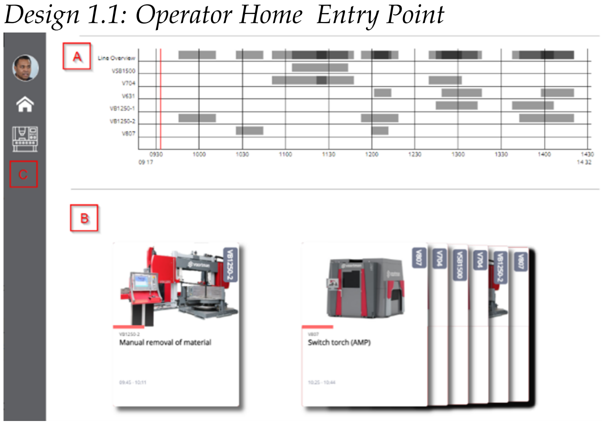
Design 1.1 is a web-based variant based on prototype 2, with feedback from both stakeholders and operators applied. Each view will be deconstructed and argued for in its own section.

7.1.1 Layout and visualization strategies

In this section, all the different visualization strategies and the general layout of the system will be described. This will be done in a per-(sub)view manner.

Figure 22

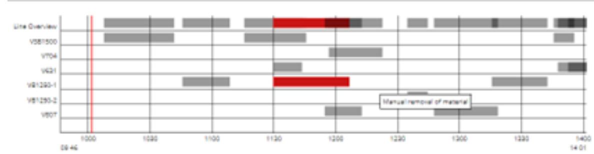
Design 1.1: Operator Home Entry Point



7.1.1.1 Operator Home (Main View / Entry point) When an operator launches the application, this is the view he or she will first see. In this view, a timeline is displayed (A), which consists of a compounded view (Line Overview) and views for each machine. If an operator is subscribed to particular machines the graphic will update accordingly. An additional filter consisting of tick-boxes can also be used to filter the output of the system. Currently this filter resides on a different page, but is intended to be placed to the left of the timeline graphic. Task cards are displayed underneath the timeline (B), and have been more disconnected from the timeline graphic. A side-menu (C) allows the operator to navigate to different views in the system, such as changing the user, viewing machine statuses, and any other additional views that are to be implemented.

Figure 23

Design 1.1: Operator Home > Timeline graphic

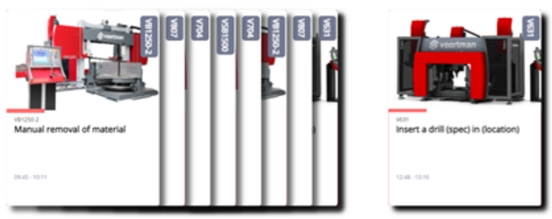


7.1.1.2 Timeline graphic The timeline graphic is mainly intended for an operator to quickly identify the flow of upcoming interventions. Hovering over a time interval will highlight the interval both in the compounded line overview, as well as in the machine view. A tooltip up containing a compact piece of information about the intervention will also pop up. Clicking the interval will bring up the related task card. Hovering over a task card will also highlight the related interval in the time line. The red vertical line in the graphic represents the current time. The graphic elements in the timeline will shift to the left along the X-axis while the red current time marker maintains to be static, preventing possible confusion, or having to look where the current time marker is located. That being said, the user is free to change the scope of the timeline, being able to zoom and drag into the future or past. This will move the current time marker accordingly, but in this new adjusted view, it will remain static in its new position.

7.1.1.3 Task Card graphic The next recommended task is presented on the left, upcoming tasks are represented as a card stack on the right. A maximum stack height can be set to prevent the stack from going of the screen if a lot of tasks are present. When this limit is reached, additional task cards will be rendered completely underneath the previous card, instead of slightly to the right. The operator also has the ability to fan through the upcoming task cards in order to look further into the future. The stack limit also applies in this case, as can be seen below. Any additional cards that will be moved to the left to look at upcoming interventions further in the future will slide completely underneath the already established stack on the left. Clicking a card in the "upcoming" stack moves any obstructing cards to the right, allowing a clear view of the clicked card.

Figure 24

Design 1.1: Operator Home > Task Card graphic



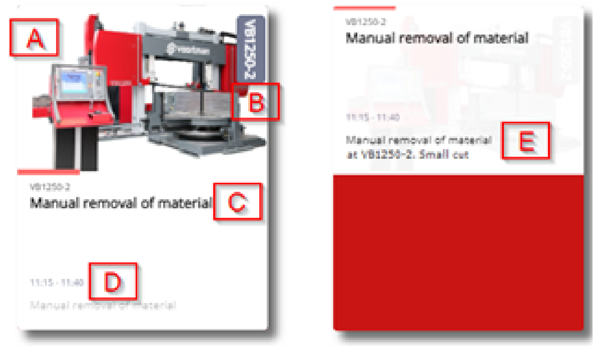
A task card contains the following elements:

- An image, this can be an image of the machine, or an icon to quickly identify the intervention (A)
- A tag, to identify at which machine intervention is needed, even if the card is further down the stack. (B)
- An intervention title (C)
- A time window in which the intervention can be executed (D)
- A more detailed description about the intervention, and why the system predicted it after clicking the card. (E)

7.1.1.4 Operator Identification To store operator preferences such as subscribed machines and to transfer them between system endpoints, a simple login system has been implemented. This will allow an operator to use any machine, even machines they are not stationed

Figure 25

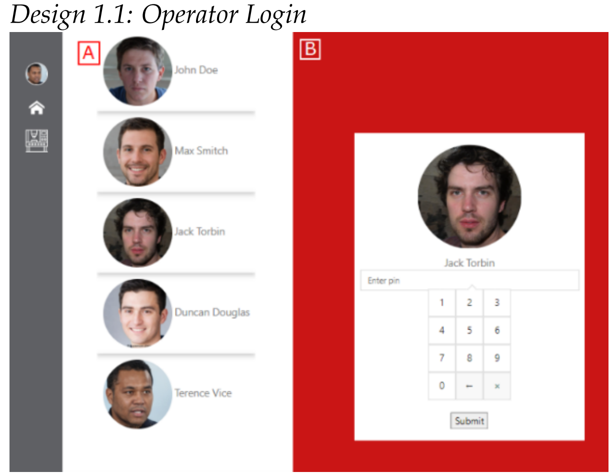
Design 1.1: Operator Home > Single Task Card



at, to quickly view their upcoming tasks.

Figure 26

Design 1.1: Operator Login



Operators can select their profile from a list (fig. 26A), after which they can input their personal pin to access their dashboard. A short pin was chosen as no sensitive personal data will be displayed, but to still serve as a deterrent to pick any operator to access the system overview. (FR5) All avatars were sourced from this-person-does-not-exist.com. Names were also generated at random. Any likeness of real persons consists purely on coincidence.

Any machine the current operator is subscribed to, includes a green checkmark in its graphic, making it easy for an operator to distinguish between them.

Figure 27

Design 1.1: Machine subscriptions

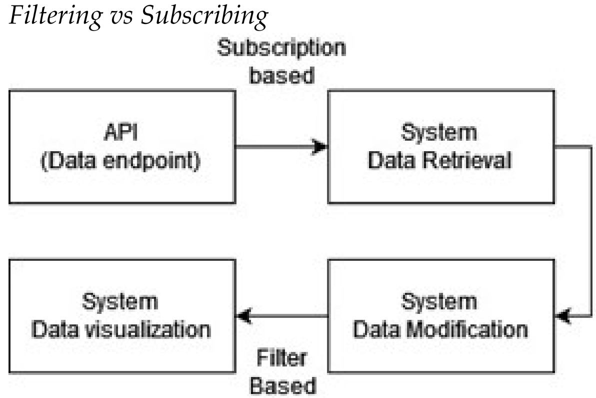
(Un)subscribing is on a toggle basis, clicking a subscribed machine will unsubscribe the current operator, and vice-versa.

7.1.2 Stakeholder Feedback on design 1.1

One critical point stakeholders attributed to is that there should be a clear distinction between filtering and editing subscribed machines. Even though the resulting visualization may be the same, there is a big difference in the underlying data manipulation within the system. To establish this distinction, both filtering and (un)subscribing will be discussed shortly: Filtering When using the filtering functionality, the system will not visualize certain elements or flows in the operator dashboard overview. Filtering should be easily accessible, as this is what an operator will want to mutate most of the time, allowing him or her to see or hide specific items in the visualization. Using this method, even if an operator decides to hide certain details for a specific machine, or everything related to a machine completely, the choice can be made for the system to override the filter for tasks that are already assigned to the operator, for that specific machine. Filtering will take place on the data after it has been requested by the system. (Un)-Subscribing Managing subscriptions should be done in a different view from the main view, in order to require a much more conscious action to modify subscriptions. If an operator unsubscribes from a particular machine, not only will the system no longer display data related to that machine (the same as in filtering), all tasks that were assigned to the operator will also be reset. Based on subscriptions, the system will retrieve specific data from an endpoint, so the option of keeping assigned tasks visible is also no longer viable. Another feature that was requested based on the subscription method is a way for operators to coordinate who is going to do which task if multiple operators are assigned to the same machine. A most suitable way to do this would be to implement this feature on the task cards.

Figure 28

Filtering vs Subscribing



Another requirement that arose from design 1.1 is to give the operators the ability to reorder machines in the timeline graphic, allowing operators to place machines they deem more important, or that require more attention, near the top of the graphic. This could help with quicker identification, as an operator wouldn't have to trace the x-axis to find which block belongs to which machines. This in itself is also an issue that could be resolved by introducing icons or tags into the time interval bars.

7.1.3 Operator feedback on design 1.1

An additional feedback session with a machine line manager was conducted at VSC, where the following feedback was acquired through a mutual brainstorming session. In order for operators to have a quicker understanding about the succession interval of tasks, without looking at the timeline, a small time indicator graphic will be introduced on the task card. For this graphic, the following was considered.

- Time should be easily interpretable.
- Actual time does not matter as much as the time between following tasks or in relation to the first task.
- Tasks that more than an hour into the future can be excluded from this functionality, as these will likely not impact an operator's planning.

Furthermore, the current subscriptions should be clearer, where the operator can see in a single glance to what machine he or she is subscribed to, instead of having to look for checkmarks. This could be solved by implementing a gray overlay over unsubscribed machine cards, indicating that they are disabled.

7.2 Design 1.2

Design 1.2 will continue the groundwork laid by design 1.1, implementing both stakeholder and operator feedback to improve on its clarity.

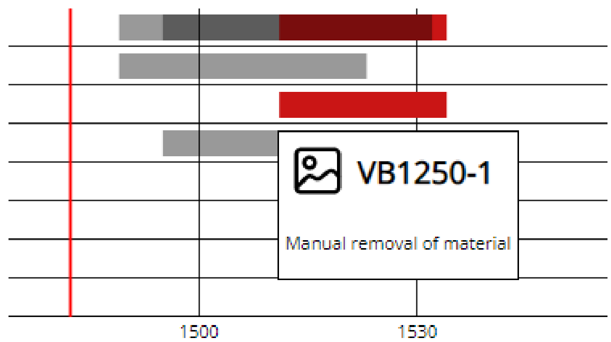
7.2.1 Layout and visualization strategies

In this section, all the different visualization strategiesand the general layout of the system will be described. This will be done in a per-(sub)view manner.

7.2.1.1 Timeline tooltips As seen in Figure 21, a small tooltip is presented to the user when hovering over a time interval. This tooltip should contain a condensed version of the detailed information found in the accompanying task card. For an operator to quickly recognize the nature of the intervention that needs to be executed, icons have been proposed. As all possible interventions have not yet been categorized, placeholders to indicate the presence of an intervention are used for now.

Figure 29

Design 1.2: Redesigned Tooltip



The redesigned tooltip also includes the name of the machine where the intervention needs to be executed and will contain a short description of the activities to be done.

7.2.1.2 Task cards In addition to the icons being added to the tooltip, the same icon will be present in the corresponding task card, both for continuity and clarity, as well as for quick identification. The task cards also have been updated to include time intervals relevant to the current time for quick identification when the intervention is to be expected.

Current intervals are: [Available, 5, 10, 15, 30, 45, 60]. If a task can be done, it will include the tag "Available". In order to prevent further screen clutter, only one card

Figure 30

Design 1.2: Redesigned Task Card

can have any of the other existing intervals, indicating that each card with an interval tag until the subsequential card with a tag are in the same interval. E.g., a card with the interval tag [15], and all additional cards until another card with an interval tag indicates that all these cards are in the interval [15-30] minutes from the respective current time. If an interval is not present, for instance [30] in the figure above, no task is present in this interval [30-45].

7.2.2 Further design choices based on design 1.2.

To increase the intuitiveness of the system and to give the operator the opportunity to quickly identify the nature and accompanying task of an intervention, an icon set was proposed. This icon set needs to be clear and self-explanatory. In order to develop icons for all possible intervention, a mapping of all possible (sub)-categories of interventions is needed. In addition to this, (sub)-tasks have been identified that are applicable at the machine line at VSC (table 8). Together with operators and in-house UI-experts, the following icon set was designed (fig. 31).

Table 8

Intervention categories and tasks at VSC, as from talks with operators.

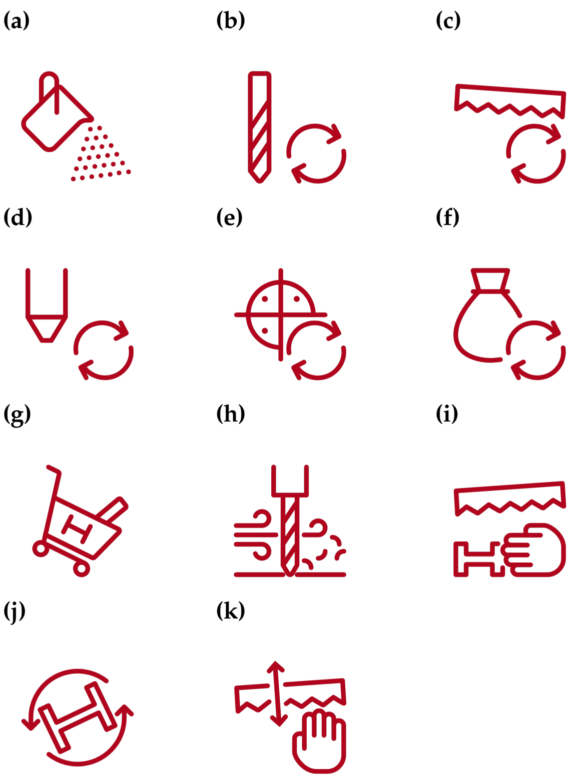
Category	(Sub) tasks at VSC	fig.
Consumable Change	Replenishing grit at shotblasting machine	fig. 31a
	Changing drills in drilling machine.	fig. 31b
	Changing saw blade at saw machine	fig. 31c
	Changing plasma cutting head at plasma cutter.	fig. 31d
	Changing scribing head at scribing machine.	fig. 31e
Clean up of debris / material	Empty dustbag at shotblasting machine.	fig. 31f
	Empty residual material bin at sawing machine.	fig. 31g
	Remove steel shavings at drilling machine.	fig. 31h
	Remove small material manually at sawing machine.	fig. 31i
Manual labor operation	Rotate beams along z-axis to align zero line at transverse belts	fig. 31j
	Saw in intervals for beams with large y- or x- dimension	fig. 31k

8 Final Design

As per all the feedback acquired so far in this research, a small inventory will be taken before starting the design

Figure 31

Action icons



Note: A special thanks to Erik Dijk from VSG for taking the time to redesign these icons.

process of design 2.1. As this will be the basis for the final design, and given all the prior research that has been done so far, research questions will also be answered in this section before starting the new design.

8.1 New task visualization strategy.

After thorough research and collaboration with operators, we have settled on a new manner of visualizing upcoming tasks, with respect to a timeline. We found that in the first design iteration, there can be a lot of unused space, while cramming information in a singular bar, increasing the complexity of the interface. This results in a loss of detail and more cognitive strain (L. Wu et al., 2016) Trying to present information in a small space can also have a negative effect on usability and performance, while also creating frustration in users (Chittaro, 2006; Yost & North, 2006). Reducing cognitive strain by allowing elements to size to their available space can also improve the decision-making process of an operator (Falschlunger et al., 2016). More on the automatic sizing of elements can be found in **??** 8.4.1.1. Using different encodings and icons within the visualization, a strong link can be created between the operator and the different manufacturing domains. Taking 2 as a reference, the visualization applies to the following elements:

8.2 Information to be displayed in the visualization for well-informed intervention execution.

After talks to multiple machine operators from different locations, we have concluded that the following information should be included in the visualization:

Table 9

Link between the dashboard visualizations and the manufacturing domain.

Visual element	Element in manufacturing domain
Color in time-line block and task-card.	Resource: Machine
Action-icon in block and task-card.	Human Activity: Manual Task
Additional icons in block and task-card.	Material: Goods, raw material, parts Resource: Tools, Consumables
Time-frame.	Resource: Time
Expanded task-card	Information: Machine data

Location

The machine at which the intervention is to be executed. This can be further expanded upon, as larger machines can consist of multiple units that need to be accessed from different locations.

Task

As tasks can vary between machines and interventions, a clear indicator should be given for what tasks need to be executed during the intervention. As tasks can also differ in execution length, a metric can be applied to inform operators of a "latest possible execution" time before the machine will stop on its own. However, mapping the duration of every single task, as they can also differ between operators and industries, is outside the scope of this research.

Tools / Consumables

Tools and/or consumables an operator will need to execute the intervention. When known beforehand, these can be prepared or called for if not available.

Priority

Some intervention tasks can have a higher priority than others, especially when multiple interventions are expected within the same time frame. Priority can be calculated based on a heuristic rule set, or other parameters, depending on the assembly-line layout and/or industry. Interventions that have a higher impact on the assembly line when their delay is executed should have a higher priority over others.

Skillset

In some cases, certain machines can require operators trained for specific circumstances. For these interventions, it is crucial that this is known beforehand, as not any operator could execute this intervention. Specialty can be assigned from a dictionary or list, by checking interventions against them.

Machine data

In some cases, the system will predict interventions based on the lifetime of consumables. These predictions may not always be accurate, as wear and tear of consumables can vary greatly through the assembly process. Machine data should be presented for the operator to make a well-informed decision on if an intervention is necessary. An example of this could be the number of holes drilled, or surface area cut. Armed with this information and a potential visual inspection of the consumable, the operator can choose for an intervention to be executed or suspended.

(Suspended) Activity

Information can also be given on what activity is expected to be suspended due to the need for intervention. If an operator notes that this suspended activity is related to a crucial part, the intervention can be executed beforehand, to minimize the manufacturing delay on the crucial part. Furthermore, if an operator decides to stop a machine to execute an intervention task, knowing what manufacturing task the machine is currently executing might be beneficial.

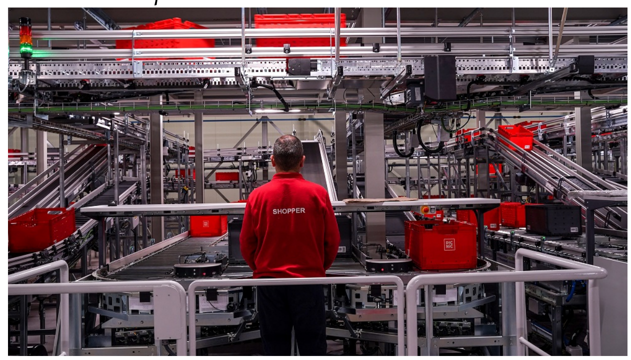
8.3 Encountering Interventions

At the moment, operators at Voortman and other companies using their machines are not notified of interventions beforehand. A machine will display a blue light when in need of an operator, or orange when a stop flag is triggered. With the implementation of our system, an operator can see upcoming interventions on a display, which is stationed already at every machine. Furthermore, the system could be ported to mobile devices, allowing for notifications when an intervention is expected within a certain timeframe. The current procedure for dealing with interventions is, that when an operator sees that a machine is in need of intervention, either through the light-pole system or by chance, he or she will approach the machine and check the display. On the display, there will be a small pop-up, indicating which task(s) need to be completed in order for the machine to resume its activities. If materials are required, an operator will fetch and or prepare these materials on the spot to be used in the execution of the intervention.

Operators in the packaging industry (“Packaging at its best - Niverplast B.V.”, n.d.) encounter interventions in a similar manner. To get a clear view of the intervention process in this industry, a visit was made to Picnic, an online e-commerce supermarket, specialized in just in time packing and delivery of groceries. To ensure a smooth packing process, multiple Niverplast machines are used to place plastic bags in so-called "totes", which resemble crates. These bags are then filled with groceries by order pickers. Machine operators at Picnic also

Figure 32

An automated production line with Picnic totes.



Note: Taken from: https://twinklemagazine.nl/2021/06/picnic-bouwt-geautomatiseerd-dc-in-ridderkerk/

get notified by a light pole system, with an additional white light to indicate that manual action is required. In addition to this, a notification sound is repeatedly played, until the intervention has been executed. This notification sound would not have any added benefit at Voortman, as there is far to much noise pollution for operators to hear the notification. When a Niverplast machine operator approaches the machine, they can select the event that stopped the machine from a log and they will be presented a stepwise instruction manual on how to solve the intervention. This could still be incorporated into our system to aid new operators to familiarize themselves with the machine and execute interventions more efficiently.

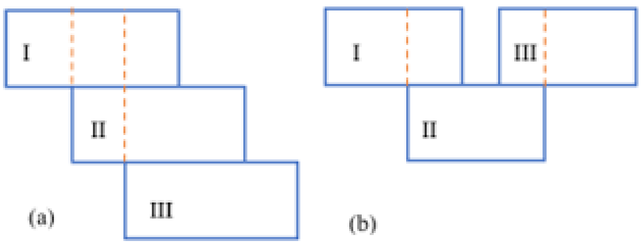
8.4 Design elaboration.

8.4.1 Layout

8.4.1.1 Dealing with overlapping interventions The new design of the timeline will allow elements to maximize their presence by growing to the available space. Operators preferred this over the earlier discussed method, as it felt less crowded, more intuitive, and less lookup is required. The width of the element is still determined by the interval in which the intervention is advised to be executed. In the case of overlapping intervals, the elements in the timeline will reshape themselves, showing overlapping elements in a stepwise manner.

Figure 33

Spacing of overlapping items



In fig. 33 (a), element I overlaps with both II and III, in such a way that a time interval "I ∩ II ∩ III" exists, whereas in (b) there are two separate overlapping intervals, "I ∩ II & II ∩ III". In the case of (a), a step-wise visualization strategy will be applied until element n, where I ∩ n is an empty set, in which case element n can be placed next to element I, as seen in (b). In the case that the width of an element is too small to accommodate an icon, the element will simply left blank. Zooming on the temporal dimension, however, would increase the width of the element and the icon and additional data will be introduced once a certain width threshold is passed. The height of a visual element, however, could pose a more serious problem, but this would only be the case if a large number of interventions would all overlap each other. As this is a scenario we do not foresee, we opted to continue with this approach. In the worst-case scenario, an operator would be able to filter machines that are no longer of interest to them, allowing for the graphic to expand by filtering out overlapping items.

8.4.1.2 Incorporating icons To make the design more intuitive and allow for faster recognition of tasks, as much information as possible is to be translated into icons. For actions to be executed during interventions, the icons in fig. 31 will be applied. These will further be referred to as "action-icons". In addition to these, two more categories of icons have been designed, static and dynamic icons. Static icons give an indication of what information is presented next to them and are not subject to any changes (fig. 38a). Dynamic icons will show necessary tools and/or consumables and will be generated based on the information presented about the intervention (fig. 38b). Furthermore, based on if an intervention has priority, an exclamation mark icon will be displayed within the task card, the task element in the timeline and on the tooltip (fig. 34c).

Figure 34

Static and dynamic icons.

(a) *Static icons for time, description, necessary tools, and location.*

(b) *Dynamic icons for required skill (V631) and necessary consumable (Drill with ⌀ 18).*

(c) *Priority icon*

Dynamic icons can be catered to a plethora of situations, such as multiple consumables with different properties. Examples of these in the case of Voortman could be: a plasma cutting head with a certain Amperage rating, steel grit with a certain level of coarseness, type of saw, etc.

8.5 Visualization strategies

8.5.1 Timeline graphic

The timeline graphics have been redesigned in order to incorporate icons, and use a color encoding in order to indicate the machine at which the intervention will take place. In addition to this, much more information is presented in a task when presented on the timeline. This information scales based on the width and height of the graphic element, omitting the least relevant information first when ample space is available. The order has been established together with machine operators, and is as follows (least relevant to most relevant (fig. 36):

- Machine tag (A).
- Necessary tools (B).
- Time interval (C).
- Action icon (D).
- Priority icon (E).

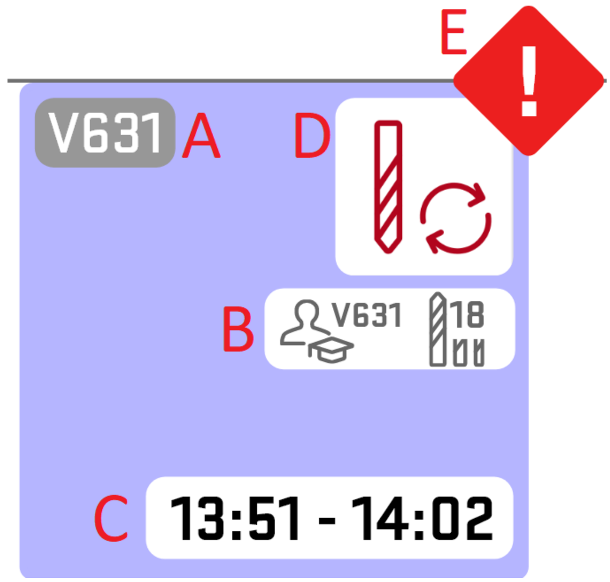
Figure 35

Redesigned timeline graphic

Zooming in on an intervention element on the timeline will therefore reveal more information about it, and all the information will always be available in the tooltip.

Figure 36

Redesigned intervention element



8.5.2 Redesigned tooltip

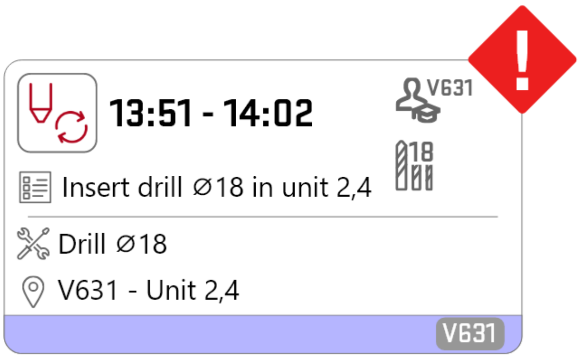
The redesigned tooltip is designed to be an equal representation of the task element in the timeline in order to give more certainty about the information displayed. This means the same color scheme and machine tags are present as in the intervention element. The tooltip displays more detailed information about the intervention without having to look up the associated task card, as its goal is to provide the operator with a short summary. The benefit of this is that less eye travel time is required, reducing gaze and lookup time if less detailed information is required (Kurzhals et al., 2015).

8.5.3 Redesigned taskcard

The principle of matching encodings between elements was also applied when redesigning the task cards. There are several encodings present to indicate a match between the intervention element in the timeline and the corresponding task card. These elements are color-encoded, text encoded, and temporally encoded. The

Figure 37

Redesigned tooltip



task card provides more detailed information when compared to the tooltip, as more space is available for this information. The taskcards have two states, expanded and collapsed, where collapsed is the default state. Expanding the taskcards by clicking on them reveals more information about the current state of the machine, but even further details could be placed here.

8.6 Design argumentation

All the previous elements tied together present the following overall look of the system (fig. 39). In this section, arguments will be made for the design choices of the final design, based on operator and stakeholder feedback and existing literature.

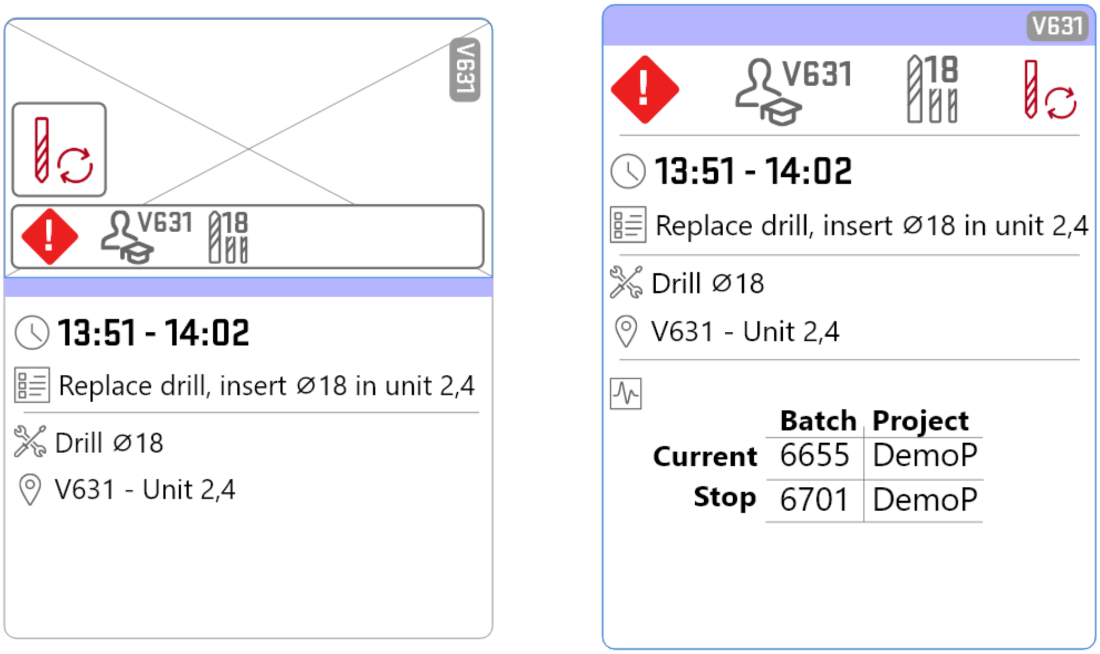
8.6.1 Applied steps from Padilla et al. (2018)

. Towards the final design the steps as suggested in the framework by Padilla et al. (2018) have been applied, resulting in the following key factors.

- Identify critical information needed for the users' task.
  The operator needs to be able to infer the time, location, tools, materials and priority of an intervention. Given the current state of the dashboard, this is possible.
- Determine which elements will attract the users attention.
  From testing with operators, it was determined that the elements in the timeline attract immediate attention, even more so if a priority symbol was present. Second, the attention shifts to the icons within a timeline element the operator deemed of interest. Lastly, the operators attention shifted to the respective task card to get more information about the specific intervention. This flow of attention is beneficial to quick information ingestion of interventions that are of interest of the operators, as it follows a top-down schema, providing more detail in each layer.
- Create a visualization that aligns as close as possible to a users' mental schema of the data.
  Operators felt that the way the information is presented to them, felt natural and fitting given the use-case. This is an argument that this step has been successfully completed.
- Reduce the number of cognitive transformation required for the decision-making process.
  As the data is presented as is, the operators are not required to do any transformation of their mental schema in order to make a decision. Information can be directly inferred from different encodings such as icons, color and placement.
- Understand of the user is using Type I or Type II cognitive processing.
  As operators wanted to be able to gain all necessary information in one quick glance, we hae focused on supporting Type I cognitive processing, supporting en giving cues to enable the operator to make a decision. However, as there might be cases where more cognitive effort and information is required,

Figure 38

Redesigned taskcards

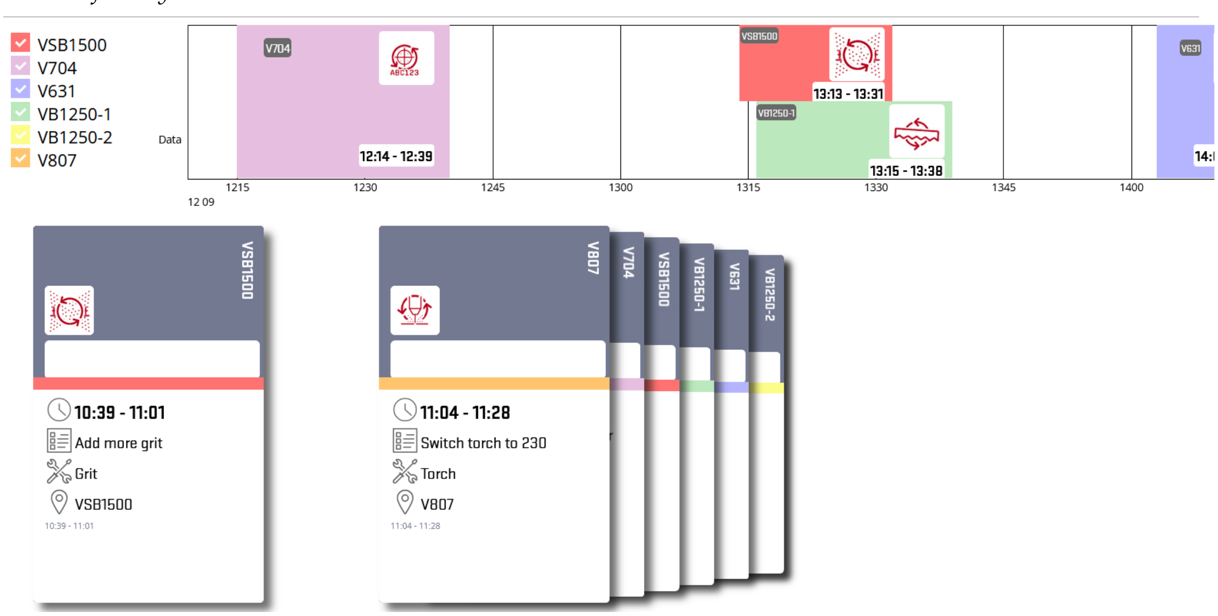


(a) *Collapsed taskcard.*

(b) *Expanded taskcard.*

Figure 39

Overall look of the system as a whole



type II cognitive processing is supported by all the additional information present in the task cards.

- Evaluate the impact of individual differences such as graphic literacy and numeracy on visualization decision making.

  The main visualization presented no issues given the graphic literacy of operators and other test subjects. That being said, the icons that represent the type and/or nature of an intervention are closely tight to the respective industry and knowledge of the user. Therefore we recommend that, when deploying a similair system, icons are designed in cooperation with machine operators to make sure they fit their mental representation of a specific action.

8.6.2 Use of icons

To convey information in the most intuitive and efficient way, as much information as possible has been translated into icons. This claim can be backed by a multitude of studies. Wiedenbeck (1999) shows that after a short learning period, icons can be more efficient than labels, or a combination of labels and icons. In addition to this, icons add a sort of signature to the software and allow for a stronger perception as opposed to using labels. Carey and Kacmar (1991) adds that iconic interfaces can be more appropriate than text-based items in disciplines such as engineering and manufacturing. Test subjects also reported a subjective preference for icon-based interfaces and icons also seemed to add to user cognition. However, as stated by Bühler et al. (2020), icons can disadvantage users if their demographics and/or capabilities differ, as their mental representation does not match the visual icon, which is also backed by Carey and Kacmar (1991). To mitigate this, all icons have been discussed with multiple machine operators and in-house UI experts. Therefore, we are confident that the icons that have been applied to the test case of Voortman Steel Group are both easy to understand and efficient for their machine operators.

8.6.3 Color encoding and visual search

The color-encoding that visually ties related elements together has been chosen from different hues, in such a way that the difference is clearly visible. Also, there is clear evidence that the matching color encoding between the corresponding parallel elements guides the user through the lookup process (Glavan et al., 2020). The current color scheme could potentially be less effective for users with color vision deficiency (CVD). In this case, a CVD-friendly palette could be applied. Users are not able to change the palette on their own, in order to avoid confusion amongst operators, as a multitude of different color schemes would reduce the effectiveness of the encoding. This argument is backed by multiple stakeholders and operators, who, believe this would also increase the complexity of the system.

8.6.4 Responsive elements and information overload

As argued before, the intervention elements in the timeline graphic have been designed in such a way that information will only be displayed when enough space is available, reducing cognitive load by lowering information density while retaining clarity, and increasing decision making efficiency (Chittaro, 2006; Falschlunger et al., 2016; L. Wu et al., 2016; Yost & North, 2006).

8.6.5 Requirement analysis

In order to check if requirements are met, a small requirement analysis using the requirements set in section 4.

8.6.5.1 Functional Requirements

FR1: Visualization of temporal data
The system is able to visualize temporal data using the timeline graphic containing intervention elements, as well as using the chronologically stacked taskcards. Operators concluded that the latest timeline design is intuitive, and data is portrayed within the exact intervention windows as dictated by the (simulated) data. On average, with cache disabled, the timeline graphics load within < 280 ms of the user requesting the page. Enabling caching lowers this number to 220 ms. The largest bottleneck in the loading speed of the timeline graphic is requesting the icons.

FR2: Show the current states of machines.
As this functionality became less and less required throughout the iterative design process, the current state of machines is not displayed at all times. However, a transitions has been made to show the current working process of a machine within the task cards.

FR3: Provide detailed information about an upcoming intervention.
The system presents all available information about interventions in a multitude of ways.

- A graphic summary using icons in the timeline graphic.
- A more detailed summary in the tool-tips.
- All details in the corresponding taskcards.

The data that is presented is not edited in any way, and is a true representation of (simulated) machine data.

FR4: Allow for grouping interventions within a similar time interval.
The system will present interventions within a similar time interval in a stacked manner, leaving the choice to the operator if these interventions should be combined into one or not. For now, no automatic grouping of interventions on a single machine within overlapping time windows is in place, but this is certainly an interesting topic to research further.

FR5: Allow for adaptive opportunistic intervention planning.
For this requirement, the same holds. There is no dedicated system in place, but interventions are presented in such a way that an operator can quickly identify interventions at the same machine to execute if possible. Developing a dedicated algorithm for this could further increase possible performance gains and may be something that should be researched further.

FR6: **- FR9:** Allow for filtering, zooming, and navigation. The system allows the user to filter and navigate both the timeline graphic and the taskcards, and allows for zooming in the timeline graphic to reveal more information within interventions elements.

8.6.5.2 Additional Secondary Requirements

ASR1: User Authentication.
As seen in design 1.1, (**??** 7.1.1.4, fig. 26), a simple form of user authentication is implemented, in order to keep track of individual preferences of operators, like machine subscriptions. These preferences can be expanded upon with settings such as preferred color palette, etc.

ASR2: Inclusion of visual cues related to tasks.
As can be seen in design 2, the visualization is far more graphic centered instead of using concise text to convey intervention information.

ASR3: Allow for feedback if an intervention was not ex-

ecuted within the predicted timeframe.
This requirement has not been implemented as time constraints prevented this. However, as stated in section 4.4, implementing this feature in later designs of the system might be benificial for optimizing efficiency and for the purpose of analysis. Therefore, further recommendations will be made in section 11: Further Research.

The overall intuitiveness of the system will be evaluated in section section 9, using both qualitative and quantitative methods. As for the response time of the entire system, a lighthouse performance score of 95 was achieved, which is considered fast by modern standards ("Lighthouse performance scoring - Chrome Developers" (n.d.)).

9 Evaluation

To evaluate the system, both a qualitative and a quantitative test were applied. As there is no reference to test the system against, the quantitative test is focused on testing the usability of the system using the System Usability Scale (SUS) by Brooke (2002). The SUS method has been a robust and reliable tool for multiple decades for testing the usability of a system (Bangor et al., 2008).

An overview of both the questionnaires for the qualitative and quantitative analysis can be found in Appendix E, Questionnaires for qualitative and quantitative analysis. Although the system is a high-fidelity prototype, its implementation at this stage was not refined enough to convince operators they were working with actual machine data, which would have induced confusion and may have impacted both the qualitative and quantitative analysis. Therefore the operators were made aware they would be testing a demo version of the system and purely focusing on its looks and functionality and not paying too much attention to details such as specific tools needed for intervention.

9.1 System Usability.

9.1.1 System Usability Scores from operators.

The operators were all given a small amount of time with the system (5 minutes) and given some simple lookup tasks depending on the visual output of the simulated data. These tasks ranged from looking up a specific intervention to figuring out what tools are needed for intervention. The performance during this task was not recorded, as it was solely meant to allow the operators to develop a feel for the system. Afterward, they were asked to both fill in the evaluation forms as found in Appendix E. The following scores were recorded on the system usability score with a sample size of 6 (table 10).

Table 10

System Usability scores from operators

Q	O1	O2	O3	O4	O5	O6	AVG.	SCORE
1	5	5	4	4	4	4	4,333	3,33
2	2	1	1	2	1	2	1,5	3,5
3	5	5	5	2	4	4	4,17	3,17
4	1	1	1	3	2	2	1,67	3,33
5	5	5	4	3	3	4	4	3
6	2	1	2	3	3	2	2,17	2,83
7	5	5	4	4	4	4	4,33	3,33
8	1	1	2	2	2	2	1,67	3,33
9	5	5	5	3	4	4	4,33	3,33
10	1	1	2	2	2	2	1,67	3,33

Note: n = 6, convenient sampling.

To determine the final SUS score, the average score from each question is calculated. Based on the question being even or odd numbered, the following formulas are applied to its average score:

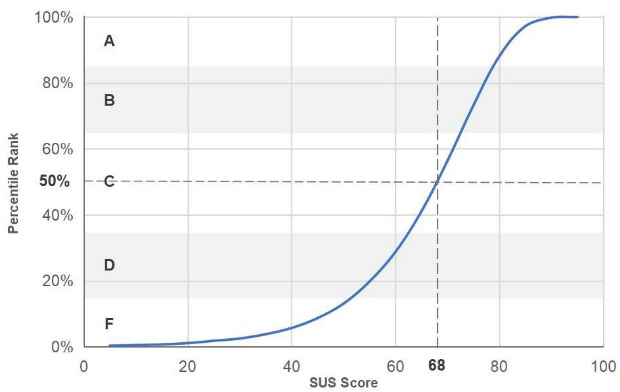
- Odd-numbered questions (Positively worded)
  $Score = avg.score - 1$
- Even-numbered questions (Negatively worded)

$Score = 5 - avg.score$

Afterward, all these scores are summed and multiplied by a factor of 2.5 to map it to a 1-100 scale, resulting in a total score of 81.25.

Figure 40

SUS score and usability



Note: Taken from "5 Ways to Interpret a SUS Score – MeasuringU" (n.d.)

As can be seen from fig. 40, a score of 81.25 places us in the 90-95 percentile range, which can also be classified as almost excellent, according to Bangor et al. (2008).

To see where we can improve on the current system, the scores of table 10 can be further evaluated. Q6, concerning the consistency of the system, has the most room for improvement. We suspect that the dynamic presentation of information based on available space in intervention elements is the leading cause for this feeling of inconsistency, but this hypothesis needs to be explored further.

9.1.2 System Usability Scores from random users.

To ensure a high base usability, users with no knowledge of underlying processes should still be able to navigate the functionalities in the system. Therefore, an additional quantitative usability test was conducted on randomly sampled test subjects. These subjects are given a small introduction to the background of the system for the subjects to understand the goal of the visualizations. The remainder of the evaluation will follow the same structure as the usability test for machine operators.

9.1.2.1 Results. Using a sample size of n=28 a score of 78.6 has been found. These results also indicate a high usability of the system, even for users who have no experience with process- and/or machine management.

9.2 Qualitative analysis of the system.

9.2.1 Qualitative analysis from operators.

Based on the answers given in the second part of Appendix E, a qualitative analysis is conducted using NVIVO ("NVivo - Lumivero", n.d.). NVIVO allows us to encode key features in the answers of operators. These key features can be analyzed to get a clearer insight into how operators feel about the system and if they feel there is any added value in using the system, and if the system will aid them.

9.2.1.1 Key insights After analyzing the interviews with operators, the following key insights arose:

- Efficiency in intervention execution.
  Operators feel that they will be better prepared and can execute interventions faster.
- Higher line throughput.
  Operators feel that interventions can be executed faster and at ideal times within the intervention time frame, resulting in increased assembly-line throughput.
- Less physical and mental stress.
  Operators feel that the system will reduce cognitive stress, as information does not have to be kept in

mind, and reduce physical stress by reducing unnecessary (long) walks, checking on machines, or fetching tools.

Machine operators noted that the system would allow them to execute interventions more specifically, with more prior information, and more efficiently. Additional information about interventions allows the operator to prepare materials and/or consumables, and if necessary, stop the machine at an ideal time within the intervention time frame. The main benefit operators also saw in the system was the prevention of unnecessary long walks up and down the assembly line, as interventions could be executed in the order that the operator planned, minimizing travel distance between interventions and machines. It was also noted that, because the operators do not have to keep (potential) interventions in the back of their minds, they could work with less cognitive stress and therefore also be more focused on the task at hand. Overall, operators do see a lot of added value in the system.

9.2.2 In-house design expert review.

During an evaluation with Voortman's in-house design expert, the system was concluded to be a good visual aid for their machine operators. Small remarks could be made towards the look of the system not being in Voortmans corporate identity, but as this was not in the scope of this research, and a more general approach was chosen to evaluate in other industries as well, this was not an issue. Overall, a positive review with no other remarks was received. The interactive link between the timeline and task cards was praised especially, as a great deal of value was seen in this interaction from a design perspective.

9.3 Reflection based on literature.

To reflect on the design and suspected efficiency of the dashboard, literature has been selected to review the system. The literature focuses on usability evaluation (Almasi et al., 2023) and on key concepts and criteria of effective dashboards (Karami et al., 2017). Using the insights gathered in both the quantitative and qualitative evaluation, we can further evaluate the dashboard based on this literature.

9.3.1 Usability evaluation.

Almasi et al. (2023) has selected 29 articles focused on the assessment of usability evaluation criteria for dashboards and extracted the following core concepts.

- Usefulness.
- Operability.
- Learnability.
- Ease of use.
- Suitability for tasks.
- Improvement of situational awareness.
- Satisfaction.
- User interface.
- Content.
- System capabilities.

Usefulness Almasi et al. (2023) subdivides usefulness into the following criteria; task performance, effectiveness of information displayed in completing tasks, control of activities and improvement of job performance, faster task performance, and maximization of efficiency. As to the insights gained from qualitative interviews, operators felt that the system will allow them to execute their tasks more efficiently and thought the information was presented effectively. Unfortunately, due to time and development constraints, the system could not be implemented to verify this objectively.

Operability Operability refers to the levels of detail of the visualization and its hierarchical structure, relevant data dimensions, access of data on different levels of aggregation and ease of selection, user recovery speed when a mistake is made, and general user control. As the system focuses on only the temporal dimension, relevant data dimensions are sufficient. Different levels of detail are accessible by opening or collapsing task cards, and specific points are easy to identify based on set filters or color encoding. As the user control of the system is intentionally kept very basic, user error recovery is very low.

Learnability Operators felt that the system was easy to understand and that there is a gentle to no learning curve. However, the system currently does not display any help messages and/or hints to guide new users through the interface. This is something that could be improved upon.

Ease of use Operators felt that the dashboard was intuitive, easy to use, and information was easily identifiable, and no guidance from others would be required to use the system, as backed by the results of the SUS test.

Suitability for tasks As the dashboard was specifically designed with the planning and execution of interventions in mind, which is the daily tasks of the user, operators feel that the dashboard is very supportive of their daily routine. The dashboard has also been made responsive with the default screen sizes on machines in mind, and the information that is displayed is directly related to interventions. The system does, however, lack a way to change the output of the visualization, but this is intentional, to not over-complicate the system.

Improving situational awareness Our dashboard aims to improve the situational awareness of operators by making them aware of interventions before a machine will stop its current process or break down. Furthermore, as the dashboard is to be implemented at every station within a line, the operator will have an overview of the entire line, no matter what machine they are tending to.

Satisfaction From the qualitative interviews, it seems that operators are satisfied with the dashboard. They feel comfortable using it when executing demo tasks, and thinks the features and UI are focused on aiding them with their daily workload.

User interface The system employs the following data visualization tools:

- A timeline, deploying markers at the time of expected intervention.
  These markers are color coded to refer to a specific machine and contain additional information about the action that needs to be performed, and what resources are needed.
- Task cards, in chronological order.
  These task cards directly relate to the marker in the timeline, and contain additional information such as the current ongoing process, the process that will induce the intervention, and more details about required tools and/or skills.

Content Operators feel that both the quality and the quantity of content is tailored appropriately to their specific task, and are able to request additional information by expanding task cards. Furthermore, they feel that the way the information is presented is comprehensive, compact and relevant.

System capabilities The system achieves its goal of aiding operators, while keeping a snappy response time and having all the necessary functions and features in place. However, certain features could be added to further aid in the decision making of operators, such as a what-if analysis tool. This idea will be expanded upon in section 11.

9.3.2 Criteria for an effective dashboard

. Karami et al. (2017) identified 56 criteria and asked experts in different fields and end user to rank these criteria based on their perceived importance. These criteria can be broken down in 7 categories.

- User customization.
- Knowledge discovery.
- Security.
- Information delivery.
- Visual design.
- Alerting.
- System connectivity and integration.

We will shortly discuss all the criteria that are applicable to our dashboard how they relate to our dashboard (with the exception of the category of user customization and security). By doing so, we hope to gain a better insight in the expected effectiveness of the dashboard. For each section we will list the met criteria against the total amount of (relevant) criteria.

Knowledge discovery. 3/5 (4 relevant) Drill down features are included in our dashboard by virtue of the link between the timeline and the taskcards, as well as by expanding the task card. Furthermore, a more standardized drill down analysis function could be included in the dashboard in the machine view, allowing operators to see what interventions have been occurring at what machines. The same goes for dimensional modeling with hierarchies and levels. As briefly discovered in the first prototype, a factory > line > machine section layout can be implemented for larger operations. Currently there is no dependency or what-if analysis, however, when this was discussed with stakeholders, there is a potential benefit implementing a what-if analysis. This will be further discussed in section 11. Moving from a monitor to analysis mode is currently not implemented within the system, as operators felt it would not support them in their day to day tasks, but was briefly touched in the first prototypes and could be implemented if necessary.

Information delivery. 2/8 (2 relevant, reporting excluded) We feel confident to say that the criteria for reasonable response time and latency has been met. Customized layout of metrics for print is not applicable to our dashboard, as it is not used for later analysis and discussion. For the same reasons, an export functionality is also not implemented. Data filtering is implemented, operators can choose to (not) view specific machines. All other criteria in category relate to reporting and exporting, which are not relevant to our dashboard.

Visual design. 8/10, (8 relevant) Our dashboard does include visual intelligence to highlight areas of interest, and indicate higher priority. The chart and information are both presented in the same screen for quick access to relevant information. Toggling between a chart and a table view is not applicable in our case, as we discovered that a timeline is the only viable option for the visual encoding of the highly temporal nature of our data. Resizing, maximizing and minimizing are implemented as the dashboard shapes itself based on the available space on the users screen. However, we have made a conscious choice to not allow for customizable or different layouts, to keep a steady user experience among different operators and low learning curve. In the sense of explainable algorithms, the system will be able to present why it expects an intervention at a certain interval, increasing its credibility and operator trust in the system. The entire dashboard fits on a screen without the need for scrolling. Meeting set objectives and metrics are not applicable to our dashboard, these criteria will not be evaluated.

Alerting 8/10 (8 relevant) Alerts are defined as a visual element within the dashboard, with exclamation marks for interventions with a high suspected priority. These support the already existing lightpole alert system. Alerts are based on how much time is left when an intervention should be executed, and can be set to any arbitrary value, although we recommend keeping this value below 5-10 minutes. That being said, these alerts are not always necessary, as an operator can already predetermine an execution schedule from the timeline. Currently, no phone alerts are integrated within the system, as we believe this could only distract operators from their work, and screens on which the dashboard can be viewed are already in place at any workstation the operator might be. The alerts do also show information about a next step, given they list the expected intervention, and how to resolve it. Email and pager alerts are not relevant to the system.

System connectivity and integration 5/6 (5 relevant) Our system has been designed with connectivity to datasources in mind. These can range from a (NO)SQL database, to extracting expected interventions directly from an operations list of a particular machine. As the system is currently based on NodeJS, a framework which will provide an http(s) endpoint containing the dashboard, every system that has the ability to access the internet and display web-pages (including running javascript) can display the dashboard, achieving a high grade of inter-OS compatibility. As the system can re-extract features from lists and or databases in the event of a shutdown, crash, or reboot, the dashboard is resilient against system errors. Furthermore, the system does have the ability to interface with a multitude of API's and protocols such as MQTT, allowing for expansions using custom code. As portals are not relevant to this usecase in this particular scenario, it has been left out of scope.

9.3.2.1 Criteria met. In total, 26 out of 27 criteria we deemded relevant for this research have been met, further strengthening our stance on the benificial effect of a possible implementation of this dashboard.

10 Conclusion

In conclusion, to design a visual aid to assist operators in the decision-making process for the execution of manual interventions in assembly line processes, the following things have been evaluated.

- What is the best fitting visualization strategy?
- How do operators encounter interventions, and how can we change and/or support this?
- What information is valuable to an operator to execute an intervention at a machine as efficiently as possible?

As for the temporal nature of the interventions, we believe a timeline is the best visual element to represent intervention interval windows. In order to provide more detailed information without overloading timeline elements, a linked cards system was introduced. These cards are also in chronological order of intervention and can be navigated using the elements in the timeline, as well as arrow keys or swiping on touchscreen-based devices. Using this strategy, an operator can quickly identify upcoming interventions and get additional information by looking at the tooltip, or by clicking the element to activate the corresponding task card. The intuitiveness and efficiency of this system has been proven by the system usability scales in section 9.1.

Most operators encounter interventions either by keeping track of the machine's state in their mind, or by intermittently looking at light poles stationed at machines, conveying the machines' current state. As it is not the intention of this research to improve how well operators can tell if a machine requires intervention, but rather aid them in the planning and execution of intercentions, the existing light pole system will stay in place. But to further support this feature, and allow operators to see if an intervention is necessary in the future, the color-coded elements in the timeline allow the operator to quickly identify when and what intervention will be necessary at what machine, increasing their awareness and effectiveness.

As stated in section 8.2, there is a non-exhaustive list of information an operator might want to be well prepared for executing an intervention. The ones below are the main ones identified within the assembly process at VSG:

- Location.
- Task.
- Tools/Consumables.
- Priority.
- Skillset.
- Machine data.
- (Suspended) Activity.

For a more comprehensive explanation of this list, please refer to section 8.2.

Using this research, we believe valuable information can be extracted from machines and molded into a dashboard to assist operators in planning and executing manual interventions, regardless of the industry. Using the designs described above, and recommendations for further research, we can comfortably state that machine operators will see the system as a valuable asset over existing software and/or infrastructure, reducing both physical and mental stress, allowing for quick learning and (most likely) increasing the effeciency of an assembly line.

11 Further Research

11.1 Expanding on the system

As this system does not present any new novel visualization strategies, but rather focuses on finding the best method to visualize expected interventions in the process industry, additional research will be required in order to port the proposed version of the system to different industries. As the system can form a good basis to build upon, different actions and structures of machine data can result in the fact that elements of the system need to be redesigned.

11.1.1 What-If analysis

In talks with operators and stakeholders it was determined that the implementation of a what-if analysis could be beneficial, as operators could determine the impact of scheduled intervention execution beforehand. This means a better understanding can be gained of the impact of the execution of an intervention in the assembly process, at any given time as set by the operator, resulting in more ideal planning and higher troughput of the assembly process.

11.1.2 Task Assignment

For larger assembly-line-based processes, it might be beneficial to reincorporate the (automatic) assignment of tasks to operators. The assignment of these tasks can be based on the location of the interventions and the sections operators are responsible for. As the planning of human resources was outside the scope of this research, it is not used in current designs. That being said, operators and stakeholders saw a lot of possible advantages in automatic human resource planning.

11.1.3 Instructional cues

As seen in machines from the packaging industry ("Packaging at its best - Niverplast B.V.", n.d.), instructional cues can aid operators to tackle interventions in a step-wise, well-informed manner, as well as aiding new operators who are not familiar with the specific machine yet. Niverplast deploys this by showing a 3D model of the affected components in the machine, highlighting the problem area, and giving a problem-solving flowchart. We recommend incorporating this in the current design of the system, as we believe this can increase the efficiency of intervention execution, especially among new operators. As an added benefit, this will allow operators to tackle more technically advanced machine faults without the need for additional (external) support.

11.2 Implementation of the system

In order to implement the proposed system, additional research and software development is required. The system uses the following parameters to visualize expected interventions:

- Intervention description
- Time interval window [start - end]
- Machine / location
- Necessary tools
- Priority
- Skill needed

The intervention description can be extracted from the existing machine date, based on the lifetime or changing of consumables. The time interval window can be predicted based on the current time, the process the machine is currently working on, and the expected ETA of the process that will require intervention before it can be executed. Machine or location is rather trivial, as this will be the source of the machine data in which an intervention is predicted or found. Based on the extracted intervention description, a link can be made to a dictionary that will cite the necessary tools and/or if a particular skill is required. A heuristic rule set can be applied to determine if an intervention will be given a higher priority. This rule set, however, can be very process- and company-specific, as these can have different preferences for assigning priority.

11.3 Placement of the systen

During rigorous talks with operators, the placement of the system was brought up multiple times by the operators. They felt that placing additional screens would just distract them more from their current responsibilities. Therefore, they agreed that the system should be implemented on screens already available at the machines, making the system accessible through a menu or button. As these screens are already in use to monitor a singular machine and its process, operators felt that this would induce the smallest possible additional workload with the greatest benefits.

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Nomenclature

Abbreviation	**Definition**
ASR	Additional Secondary Requirement
FR	Functional Requirement
NFR	Non-Functional Requirement
OOD	Object Oriented Database
RQ	Research Question
SIR	Software Implementation Requirement
SRP	Software Requirement Prioritization
TFN	Triangular Fuzzy Number
CVD	Color Vision Deficiency

Appendices

A Tables from "A review of data visualization: opportunities in manufacturing sequence management" (Sackett et al., 2006)

Table 3. Visualization functionalities and functional requirements.

		Functional requirements					
		Dynamically update with manufacturing sequence data	Highlight areas where problems consistently occur	Communicate current and predicted production status	Address different levels of decision makers	Communicate information with suppliers	Deal with complex and disparate software/databases
VISUALIZATION FUNCTIONALITIES	Focus attention (DeSanctis 1984, Vessey 1991, Foil and Huff 1992, Mackay *et al.* 1992)		X	X	X	X	
	Trigger memory (Tan and Platts, 2003a)	X	X	X			
	Share thinking (Eden 1988, Foil and Huff 1992)				X	X	X
	Stimulate thinking (Tufte 1990, Kim and Mauborgne 2002)		X	X			
	Bridge missing information (Tegarden 1999)	X		X			X
	Challenge self-imposed constraint (Morgan 1998, Mintzberg and Van der Heyden 1999, Davies and Mabin 2001, Tan and Platts, 2003b)		X		X	X	
	Identify structure, trends and relationships (Weick 1979, Zhang and Whinston 1995, Chen 1999, Mintzberg and Van der Hayden 1999, Kaplan and Norton 2000, Phaal *et al.* 2004)	X	X	X	X	X	X
	Display multivariate performance (Mills *et al.* 1998, Richards 2000, Kim and Mauborgne 2002)			X			X
	Highlight key factors (Tufte 1983, Eden 1988, Tan and Platts 2003a)		X				
	Provide an overview of complex data sets (Horn 1989, Tufte 1990, Spence 2001)			X			X

Table 4. Visualization techniques and functional requirements.

		Functional requirements					
		Dynamically update with manufacturing sequence data	Highlight areas where problems consistently occur	Communicate current and predicted production status	Address different levels of decision makers	Communicate information with suppliers	Deal with complex and disparate software/databases
VISUALIZATION TECHNIQUES	Projection (Asimov, 1985)	X		X	X		X
	Filtering (Spoerri 1993, Becker *et al*. 1995, Tang *et al*. 2002)		X	X	X	X	X
	Zoom (Rao and Card, 1994)		X	X	X		
	Distortion (Spence and Apperley 1982, Alpern and Carter, 1991, Mackinlay *et al*. 1991, Sarkar and Brown 1994, Munzner and Burchard 1995)		X	X	X		X
	Link and brush (Lopez *et al*. 2002, Tang *et al*. 2002)	X				X	X

Table 5. Applications and functional requirements.

		Functional requirements					
		Dynamically update with manufacturing sequence data	Highlight areas where problems consistently occur	Communicate current and predicted production status	Address different levels of decision makers	Communicate information with suppliers	Deal with complex and disparate software/databases
APPLICATIONS	PROCESS MONITORING	Sackett and Williams 2003a	Farrell and Zappulla 1989, Gazmuri and Arrate 1995, Przechocki 1998, Hameri and Nihtila 1998, Nottingham *et al.* 2001, Sackett and Williams 2003a, Tien-Lung 2003, Cook *et al.* 2004	Farrell and Zappulla 1989, Bassett 1995, Hameri and Nihtila 1998, Przechocki 1998, Skarlo 1999, Sackett and Williams 2003a, Tien-Lung 2003, Cook *et al.* 2004, Jorgensen *et al.* 2004	Farrell and Zappulla 1989, Gazmuri and Arrate 1995, Hameri and Nihtila 1998, Przechocki 1998, Skarlo 1999, Yafang and Yongwei 1999, Nottingham *et al.* 2001, Sackett and Williams 2003a		Farrell and Zappulla 1989, Bassett 1995, Yafang and Yongwei 1999, Richards 2000, Sackett and Williams 2003a, Tien-Lung 2003
	PROCESS VISUALIZATION		Baldwin *et al.* 1991, Zha *et al.* 1998, Hu *et al.* 2002, Groombridge *et al.* 2003	Baldwin *et al.* 1991, Lu *et al.* 1997, Hu *et al.* 2002, Groombridge *et al.* 2003, Sundin and Medbo 2003	Baldwin *et al.* 1991, Saboo and Deisenroth 1992, Alabastro *et al.* 1995, Ping 1996, Lu *et al.* 1997, Zha *et al.* 1998, Gerace and Gallimore 2001, Hu *et al.* 2002, Shires *et al.* 2002, Groombridge *et al.* 2003, Lau *et al.* 2003, Sackett and Williams 2003b, Sundin and Medbo 2003	(Ping 1996)	Baldwin *et al.* 1991, Saboo and Deisenroth 1992, Alabastro *et al.* 1995, Zha *et al.* 1998, Gerace and Gallimore 2001, Shires *et al.* 2002, Lau *et al.* 2003, Sackett and Williams 2003b
	INTERNET-BASED		Bo *et al.* 2001, Srinivas *et al.* 2001	Bo *et al.* 2001, Srinivas *et al.* 2001, Wang *et al.* 2004	Bo *et al.* 2001, Srinivas *et al.* 2001, Lee and Campbell 2003, Duffy *et al.* 2004, Wang *et al.* 2004	Lee and Campbell 2003, Duffy *et al.* 2004	Bo *et al.* 2001, Srinivas *et al.* 2001, Lee and Campbell 2003, Duffy *et al.* 2004, Wang *et al.* 2004

(*continued*)

Table 5. (*Continued*).

	Functional requirements					
	Dynamically update with manufacturing sequence data	Highlight areas where problems consistently occur	Communicate current and predicted production status	Address different levels of decision makers	Communicate information with suppliers	Deal with complex and disparate software/databases
SIMULATION		Orady *et al*. 1997, Rohrer 1997, Wen-Tsai and Shih-Ching 2003, Waurzyniak 2004	Thomasma *et al*. 1994, Rohrer 1997, Wen-Tsai and Shih-Ching 2003, Waurzyniak 2004	Hollocks 1991, Thomasma *et al*. 1994, Orady *et al*. 1997, Rohrer 1997, Setchi and Bratanov 1998, Xiang *et al*. 2002, Wen-Tsai and Shih-Ching 2003, Waurzyniak 2004		Hollocks 1991, Thomasma *et al*. 1994, Orady *et al*. 1997, Setchi and Bratanov 1998, Xiang *et al*. 2002, Adam and Mastorakis 2003, Wen-Tsai and Shih-Ching 2003, Waurzyniak 2004
VIRTUAL REALITY		Orady *et al*. 1997, Yao *et al*. 2002, Ozan *et al*. 2002 Freitag and Urness 2002, Jezernik and Hren 2003	Ozan *et al*. 2002, Wen-Tsai and Shih-Ching 2003	Chernoff 1973, Johnston and Thompson 1993, Orady *et al*. 1997, Yao *et al*. 2002, Mersinger and Westkämper 2002, Freitag and Urness 2002, Ozan *et al*. 2002, Wen-Tsai and Shih-Ching 2003, Cunha *et al*. 2003, Wiendahl and Fiebig 2003, Mujber *et al*. 2004		Johnston and Thompson 1993, Orady *et al*. 1997, Rohrer 1997, Yao *et al*. 2002, Freitag and Urness 2002, Mersinger and Westkämper 2002, Ozan *et al*. 2002, Wen-Tsai and Shih-Ching 2003, Cunha *et al*. 2003, Wiendahl and Fiebig 2003, Jezernik and Hren 2003, Mujber *et al*. 2004

B Operator Interviews

Main questions, open ended. [Dutch version below] Conversation steering questions if the conversation does not flow in that direction. Interview will be structured into two parts. Part 1 to identify what potential information an operator is missing, and Part 2 to see what would change if an operator does have access to this information. Questions will change to for e.g. “How would you like to be notified about an intervention?” and “Would you like to know the cause of an intervention beforehand?”.

Encountering Interventions

1. How does the participant encounter manual tasks / interventions when working with production line-based machines?
2. Does the participant get notified? How?
3. Where is the participant when an intervention is needed?
4. What is the context participant is working in? Mainly tending to machines / other responsibilities?
5. Layout of the machines / only responsible for a few close together or responsible for more? Shared responsibility across the workshop or sections?

Cause of Interventions

1. What are the nature of these tasks / interventions?
2. What caused the need for the intervention?
3. What is the most occurring type of intervention?
4. Is there any impact on the production process?

Dealing with Interventions

1. How does the participant deal with these tasks / interventions?
2. Is there any preparation needed to execute an intervention?
3. How do you know when to execute a intervention? Is there any systematic way of organizing them when multiple machines need tending to?
4. Is there any agreement between operators on who does what?
5. Do interventions have priority over other tasks you need to do?

Open hoofdvragen [English version above] Vragen om het gesprek te sturen als een onderwerp niet te sprake komt. Het interview wordt opgedeeld in 2 delen. Deel 1 om te identificeren wat voor mogelijke informatie een operator mist, en deel 2 om te zien wat er zou veranderen als een operator deze informatie wel zou hebben. Vragen veranderen naar bv. “Hoe zou je willen weten dat er een interventie moet worden uitgevoerd?” en “Zou je de oorzaak van een interventie van te voren willen weten?”.

Interventies tegenkomen

1. Hoe treft de operator nu handmatige interventies?
2. Krijgt de operator een melding?
3. Waar is de operator wanneer een interventie nodig is?
4. Wat is de context van werkzaamheden van de operator? Is de hoofdzaak het bedienen van machines / andere werkzaamheden?
5. Lay-out van het productie proces. Is de operator alleen verantwoordelijk voor een paar machines / een sectie? Is er gedeelde verantwoordelijkheid voor de hele hal?

Oorzaak van Interventies

1. Wat is de oorzaak van interventies?
2. Waarom is een interventie nodig?
3. Wat voor interventie komt vaak voor?
4. Is er een impact op het productie proces?

Omgaan met Interventies

1. Hoe gaat de operator om met interventies?
2. Is er voorbereiding nodig om een interventie uit te voeren?
3. Hoe weet de operator wanneer hij een interventie moet uitvoeren? Is er een systematische manier van organiseren wanneer meerdere machines aandacht nodig hebben?
4. Is er enige overeenstemming tussen operators wie wat doet?
5. Hebben interventies prioriteit over andere werkzaamheden die de operator doet?

C Balsamiq Wireframes of the second prototype

Figure 41

Operator Home

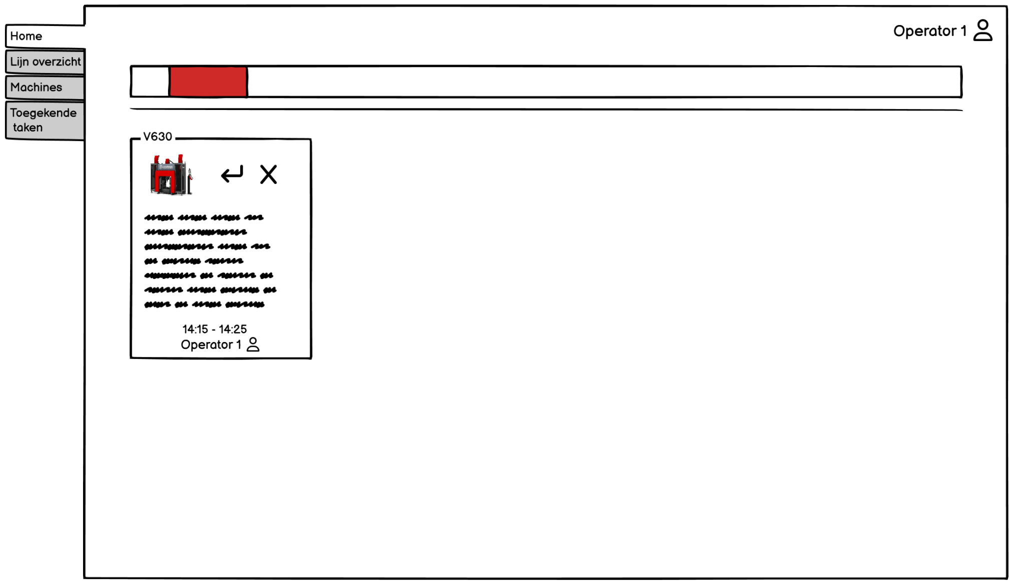


Figure 42

Line overview

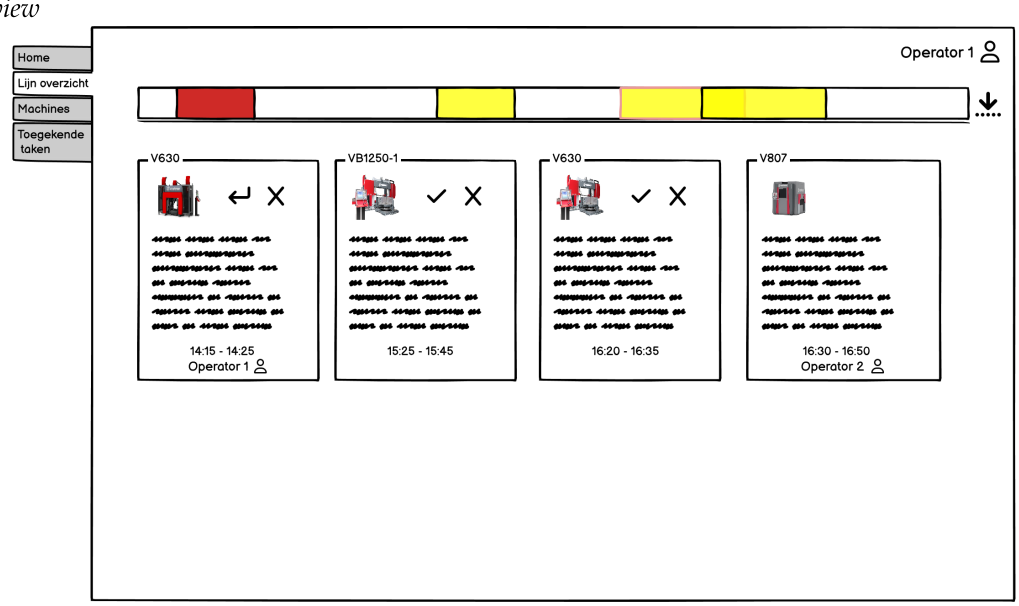


Figure 43

Line overview expanded

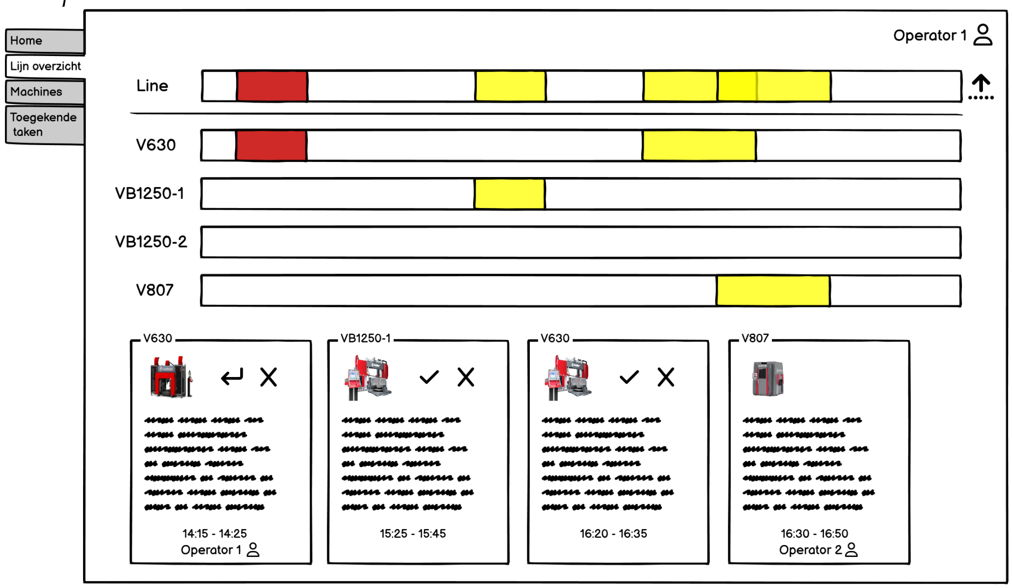


Figure 44

Machine overview

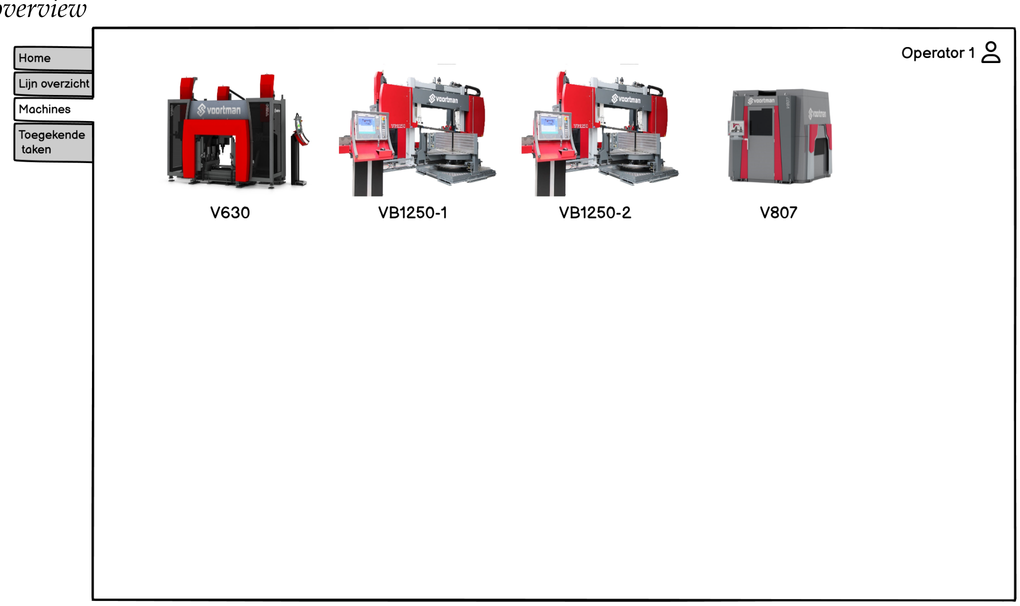


Figure 45

Detailed machine view

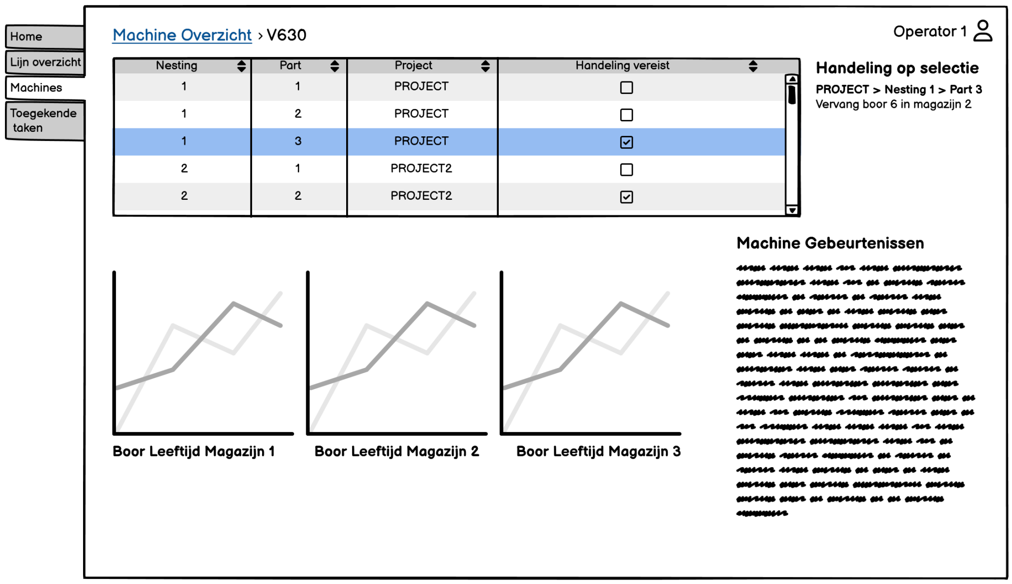


Figure 46

Allocated task view / subscription management

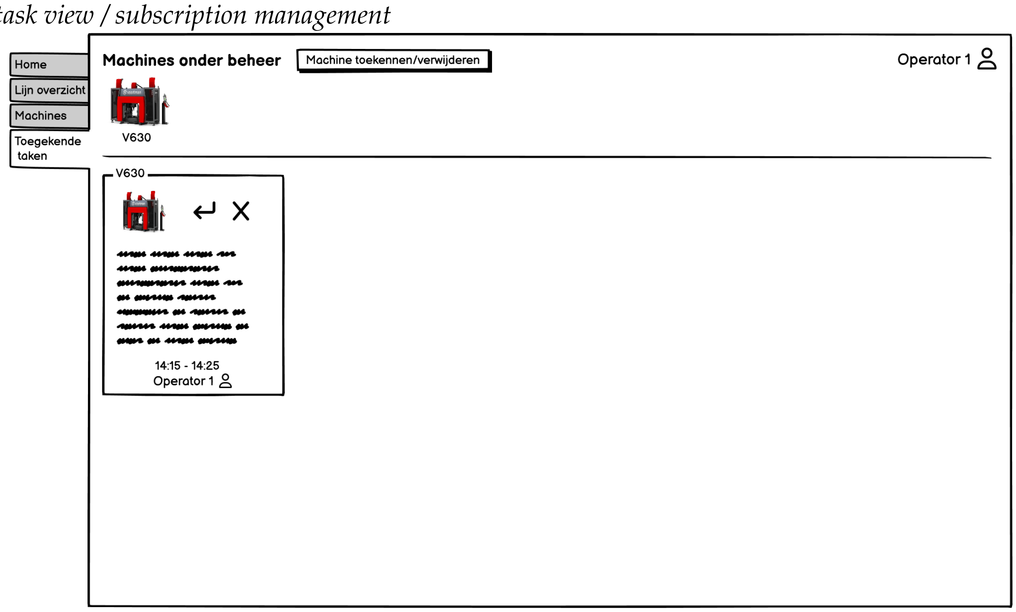
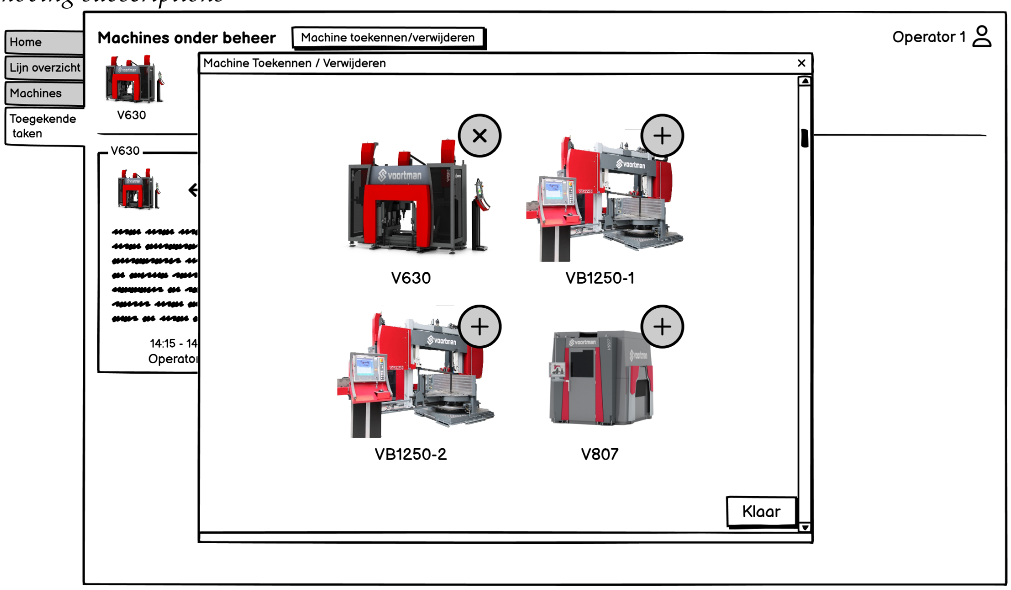


Figure 47

Adding/removing subscriptions



D Requirement Prioritization Calculation

In order to calculate the prioritization scores for Software Requirements, the following formula is applied:

$$\sum_{i=1}^{n} P_k = P(W_{FR_k} \otimes W_{NFR_i}) \text{ (1)}$$

Where P_k is the prioritization score of functional requirement k, evaluated over all non-functional requirements n, and W the Triangular Fuzzy Number respective to the MoSCoW score of FR_k in respect to NFR_i (table 3) and the Triangular Fuzzy Number respective to the MoSCoW score of NFR_i (table 4).

The summation part formula can be expanded to the following form:

$$P(W_{FR} \times W_{NFR}) = (\frac{m_1+4q_1+s_1}{6}) \times (\frac{m_2+4q_2+s_2}{6}) \text{ (2)}$$

Where W_{FR} and W_{NFR} are two TFNs (m, q, s).

For example, take a system with only two FRs and two NFRs and the following MoSCoW scores:

Table 11

Example system with 2 NFRs and 2 FRs

NFR	FR	MoSCoW
NFR1	FR1	SH
	FR2	CH
NFR2	FR1	MH
	FR2	SH

Table 12

Importance weights for NFR

NFR	MoSCoW
NFR1	SH
NFR2	MH

Evaluating FR2 would yield the following results, given the TFNs in table 3 and table 4:

$$\sum_{i=1}^{2} P_2 = P((0, 0.33, 0.66) \otimes (2.5, 5, 7.5)) + P((0.33, 0.66, 1) \otimes (5, 7.5, 1)) \text{ (1)}$$

$$P_2(W_{FR} \times W_{NFR}) = (\frac{0+4\times0.33+0.66}{6}) \times (\frac{2.5+4\times5+7.5}{6}) + (\frac{0.33+4\times0.66+1}{6}) \times (\frac{5+4\times7.5+1}{6}) = 5.62 \text{ (2)}$$

E Questionnaires for qualitative and quantitative analysis.

System usability scale questionnaire (Dutch)

	Helemaal Oneens	Oneens	Neutraal	Eens	Helemaal Eens
Ik denk dat ik dit systeem vaak zou willen gebruiken.	O	O	O	O	O
Ik vond het onnodig ingewikkeld.	O	O	O	O	O
Ik vond het systeem makkelijk te gebruiken.	O	O	O	O	O
Ik denk dat ik technische hulp nodig heb om het systeem te gebruiken.	O	O	O	O	O
Ik vond de verschillende functies van het systeem goed met elkaar samenwerken.	O	O	O	O	O
Ik vond dat er te veel tegenstrijdigheden in het systeem zaten.	O	O	O	O	O
Ik kan me voorstellen dat de meeste mensen snel met het systeem overweg kunnen.	O	O	O	O	O
Ik vond het systeem omslachtig in gebruik.	O	O	O	O	O
Ik voelde me zelfverzekerd tijdens het gebruik van het systeem.	O	O	O	O	O
Ik moest veel over het systeem leren voordat ik het goed kon gebruiken.	O	O	O	O	O

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Qualitative questionnaire (Dutch)

Wat is je eerste indruk van het systeem?

____

____

____

____

Denk je dat het systeem je kan helpen? Zo ja, hoe?

____

____

____

____

Denk je dat het systeem toegevoegde waarde heeft?

____

____

____

____

Mis je iets aan het systeem? Zo ja, wat?

____

____

____

____

Denk je dat je de adviezen van het systeem zou opvolgen? Waarom?

Zou het systeem je tijd besparen of juist meer tijd kosten? Waarom?

Want denk je dat er zou veranderen als je het systeem zou gebruiken, als je het vergelijkt met nu?

System usability scale questionnaire

	Helemaal Oneens	Oneens	Neutraal	Eens	Helemaal Eens
I think that I would like to use this system frequently.	O	O	O	O	O
I found the system unnecessarily complex.	O	O	O	O	O
I thought the system was easy to use.	O	O	O	O	O
I think that I would need the support of a technical person to be able to use this system.	O	O	O	O	O
I found the various functions in this system were well integrated.	O	O	O	O	O
I thought there was too much inconsistency in this system.	O	O	O	O	O
I would imagine that most people would learn to use this system very quickly.	O	O	O	O	O
I found the system very cumbersome to use.	O	O	O	O	O
I felt very confident using the system.	O	O	O	O	O
I needed to learn a lot of things before I could get going with this system.	O	O	O	O	O

Universiteit Utrecht

voortman STEEL GROUP

Qualitative questionnaire

What is your first impression of the system?

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Do you think the system is able to aid you with your tasks? If so, how?

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Do you think the system has any added value?

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Is there any functionality that is missing in the system? If so, what?

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Do you think you would follow up on the advice given by the system? Why?

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Do you think the system would save or add to your workload? Why?

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What do you think would change if you start using the system, compared to the current situation?

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