Designing Real Time Insights Dasboards for SME Manufacturing with Legacy Assets.

Master Thesis report

Bob Warringa

Delft University of Technology

Designing Real Time Insights Dasboards for SME Manufacturing with Legacy Assets.

Master Thesis report

by

Bob Warringa

to obtain the degree of Master of Science
in Management of Technology
at the Delft University of Technology,

Student number:	4389301
Thesis committee:	Dr. Aaron Ding, Chair and 1st Supervisor
	Prof. Lori Tavasszy, 2nd Supervisor
	Martijn Otten, 3rd External Supervisor

TU Delft

Preface

With great pleasure, I present to you my Master Thesis with the subject: "Designing Real Time insights Dashboards for SME Manufacturing with Legacy Assets". This is the result of exploratory research and deliberation in cooperation with Color Control Group, abroad and domestic.

I could not have come this far without my chair and first supervisor, Aaron Ding. Countless discussions about the framework, framing and problem driven thinking have given me the right direction for this research project. His patience with me in this journey of research and my personal development has provided me with the confidence to continue on the path of becoming Master of Science.

Thank you to Professor Lorí Tavasszy for his guidance and direction as second supervisor in this research project. He has given me the tools to be able to zoom out and avoid tunnel vision when selecting a research method and given context to the expectations of a Master Thesis.

I could not fail to mention Martijn Otten, managing director AV Flexologic, in his role as external supervisor, I'm grateful for his continued support and belief in the project. This project was initiated during my time as project improvement engineer working at AV Flexologic and together with Martijn, I have formulated the problem and tried to come up with a solution. I am very happy that I could adapt this into a Master Thesis together with the Delft University of Technology.

This research project could not have been completed without the most valuable resource available to me, the interviewees. Thank you for taking the time to talk about your personal experience with manufacturing processes and digital insights.

Many thanks for proofreading and correcting my writing, Michiel Smit and my dear sister Pommeline. Thanks to your efforts, critical thinking and editorial work. I'd like to thank my family, friends and housemates for continued support for the duration of the thesis research.

I hope that this Thesis will serve as part of the valuable resources available to those who are interested in the opportunities related to Industrial Internet of Things technologies in the manufacturing sector.

Bob Warringa
Rotterdam, September 2023

Executive Summary

Working as a manufacturing engineer in a company that geographically is located far from the production facility, it has been often hard to gain access to manufacturing data in real time. There are often a lot of calls involved and time is wasted by employees who can't afford to do so. Manually retrieving machine data displaying efficiency or getting status updates on individual parts is something that takes a lot of time. Employees will often get frustrated with the n-th question about production efficiency or individual parts status, resulting in negative communication and a falling out of the reporting system. Menial tasks are frustrating for everyone involved and automating them could be a big improvement. Middle management have a hard time getting the production data from the employees, as they are busy achieving their production targets. As a result, they cannot identify problems in the operation of their machines. Top level management suffers the same fate, leaving problem solutions to come too late to have an impact. If data does come through, it is often word of mouth, possible to be influenced by employees and middle management. Making decisions based on this data would seriously jeopardize the operation of the business unit or the entire company. *Manufacturing SMEs with legacy production assets have hardly any insights into the machine-based production process, impacting performance and flexibility*

Implementing a lightweight interface design with limited infrastructure investment connected to legacy production assets can enable real time insights into the manufacturing process. When following the best practices and design guidelines presented in Chapter 5, this aids the implementing engineering team in making prudent choices in presenting information to the right stakeholder. Having universal access to transparent production metrics can help them improve their production process and help achieve efficiency gains. Operators can plan ahead with access to planning, upcoming programs and tools. Middle management gains resource planning abilities and performance evaluation data of individual machines. Live monitoring of machine status can quickly provide intervention stimulus to solve issues faster. Top level management gains big-picture live data and can identify problems in real time. Automated reporting of manufacturing data in weekly, monthly and quarterly fashion helps track the manufacturing process over time.

The most crucial benefit of gaining real time insights in the production process has been evaluated among industry professionals, managers and the expert panel in Chapter 4 and 6. The consensus is that the ability of having objective transparent insights into the manufacturing data leads to increased production efficiency. This benefit is gained by the increased capacity to identify problems, evaluate production processes and implement process improvements. A further benefit stemming from the gain of real time insights is the improvement of communication, eliminating misunderstandings in production orders and production status.

This thesis research and its design solutions help small and medium sized enterprises gain real time insights into their manufacturing process, resulting in production efficiency gains and helping identify process improvements. These factors help manufacturing SMEs stay competitive in an ever-increasing competitive global business climate. The thesis research and the prototype designs are relevant to the field of Management of Technology in the sense that it connects technical engineering challenges to the managerial and administrative solutions of a modern connected manufacturing operation. The way this thesis is set up, is to overcome these challenges by involving relevant parties and creating a fitting for them. The outcome of these challenges are beneficial in aiding the making of business decisions based on objective data and technical knowledge.

Keywords: *Industrial Internet of Things, IIoT, IoT, manufacturing, SME, data visualisation, real time insights, legacy assets, Management of Technology, MoT*

Contents

List of Figures

List of Tables

Nomenclature

Please see the table below for explanations of various abbreviations.

Abbreviations

Abbreviation	Definition
CCG	Color Control Group
CNC	Computer Numerically Controlled
CPS	Cyber-Physical System
DSRM	Design Science Research Methodology
ERP	Enterprise Resource Planning
FAANG	Facebook (Meta), Apple, Amazon, Netflix, Google (Alphabet)
HCI	Human-Computer Interface
I4.0	Industry 4.0
IACS	Industrial Automation and Control Systems
IoT	Internet of Things
IIoT	Industrial Internet of Things
ISRF	Information Systems Research Framework
KPI	Key Performance Indicator
MS	Microsoft
NC	Numerically Controlled
SME	Small and Medium-sized Enterprise

1 Introduction

The term Internet of Things (IoT) was first used in 1999 and has been used to describe the ecosystem of connected devices in consumer, domestic, business and industrial sectors [32]. While the IoT term includes the industrial sector, the overwhelming majority of literature related to IoT is hardly applicable to the industrial sector. This is why a distinction must be made to specify the challenges of the industrial sector. Thus, the Industrial Internet of Things (IIoT) term was coined [7]. The development and adoption of Industrial Internet of Things (IIoT) has revolutionized various industries, including manufacturing. Industrial Automation and Control Systems (IACS) are traditionally isolated systems, separate from digital business networks in enterprise Information Technology (IT) environments. Where connectivity between all aspects of business operations is required, extensive firewalls are used to protect critical industrial processes. IIoT is critical in changing the architecture of IT solutions within industry and leads to better connected industrial systems.

Small and medium-sized enterprises (SMEs) in the manufacturing sector face unique challenges, particularly when it comes to leveraging IIoT technologies with their existing legacy assets. Often, these companies have an existing, old fleet of production assets. Due to the age of these legacy assets, the organization is unable to be effectively connected within modern, secure IT infrastructure. Often, production assets with an age up to 25 years can be economically upgraded to integrate into a data sharing network and be (although limited) IIoT enabled. Upgrading or replacing these production assets does raise financial barriers for the manufacturing SMEs to overcome, as does the modern, secure data infrastructure and the IIoT interface. As the average age of employees in the manufacturing sector is significantly higher than the broader labour market [28], knowledge barriers to the implementation of IIoT technologies into the manufacturing operation can be present. The state of the art technologies are not known to the employees, so possibilities for innovation are left un-utilized. Being late to adopt these innovations isn't necessarily a disadvantage, as learnings can be taken from early adopters. Current IIoT developments can be directly implemented into the systems, skipping high early-adopter costs. Digitisation in the manufacturing sector has not been a fast process, but has slowly cemented itself in factories small and large. This provides opportunities for the implementation of further digitisation and automation, due to lower financial barriers previously difficult to overcome for SME's. As data is already being generated by the vast majority machine tools in the production process, the next challenge is to use the data in a meaningful way.

This thesis aims to explore the implementation of IIoT technologies in SME manufacturing to gain real-time insights, improve operational efficiency, and enhance decision-making processes. Real-time machine data insights offer a transparant and unbiased perspective into a manufacturing production process, enabling the identification of issues and the improvement of the production process.The research investigates the potential benefits, challenges, and strategies involved in integrating IIoT technologies with legacy assets in SME manufacturing environments. This is all integrated into a prototype design for a Human-Computer Interface (HCI) which displays relevant data to the appropriate stakeholder.

1.1. Motivation

This research has been primarily motivated by my experience of facing the challenges related to providing clear and impartial overviews of the production process and accurate output figures. Working in a manufacturing SME as a manufacturing engineer, this gave ideas on how to manage and overcome these problems and provide insights into the manufacturing production chain. SMEs are often operating on legacy assets, such as old milling machines or lathes. There are often already functions built into these devices to extract production data out of them. If this is not the case, a data extraction tool (e.g. a sensor) would be necessary to get real time insights from these kinds of machines.

Interviews have been conducted by the researcher to gauge interest and opinions from production managers, directors, systems engineers and operators. The systems engineers have indicated their concerns regarding information security, legacy device protection and stressed the importance of production data insights. Managers have indicated that the lack of transparency limits their ability to give their output-dependent team-members (such as sales personnel) accurate forecasts of output. The production manager would like to accurately gauge employee and machine performance, but is limited by time consumed with other tasks to gather and aggregate the necessary data. Visualising the production data generates value in the reduction of waste: asking a colleague for output figures or a production report would largely be unnecessary as the desired information would be readily accessible.

1.2. Gaining real time insights into SMEs with legacy assets

This section discusses the exploration journey from the top level vision of lean manufacturing to arrive to gaining real time insights into SMEs with legacy assets. An illustration (Figure 1.1) is given for a broad overview of the journey traveled. This is representative of manufacturing SMEs adopting the Lean manufacturing concept.

Figure 1.1: Problem journey, adapted from [38], [25] and [35]

The ability to act quickly on changes in production and solve problems is paramount in a manufacturing operation. These unobstructed transparent manufacturing data insights give a lot of information in meta of what is actually being produced. Having the ability to react to the presented data in real timegives a company flexibility and allows it to quickly make interventions and solve problems.

1.3. Problem

When designing for a modern and competitive manufacturing operation, one cannot ignore Industrial Internet of Things innovations if a lasting competitiveness is to be achieved [43]. Small and medium sized manufacturing operations have been followers in the process of adopting industry 4.0 principles compared to large enterprises. Over the past few years, adoption of these idea's and technologies has been on the rise [24]. In recognition of the flexibility, cost, efficiency, quality, and competitive advantage benefits these innovations bring, more than half of manufacturing SMEs have implemented one or more technologies linked to industry 4.0 and thus are interested in the benefits this umbrella of technologies brings. However financial and knowledge constraints are hampering the pace of implementation and can offer insurmountable barriers to entry.

European manufacturing SMEs are struggling with identifying suitable innovations and managing the resources required [12]. Tools like [12] and [2] have been developed to help managers identify key characteristics of their business, the stage in which they find themselves and logical next steps to take. Lacking in this field are practical tools that incorporate these parameters and can directly provide guidance to managers in their choices of innovation. Existing tools don't necessarily evaluate the outcome of individual data and provide metrics to be used in performance evaluation.

At the core, this research would focus on aiding the design of material and process flow within a manufacturing operation, requiring existing inputs and metrics provided by the operation themselves. These would be linked to established data such as [12] and [2] to output innovation options. Financial consequences of these investment proposals should be a key output of this research is to aid managers to make investment decisions based on hard data. Data and processes should be anonymized and shared between users so a continuously improved aggregated visualisation of the proposed innovations can be realized.

To enable manufacturing SMEs previously unable to innovate due to knowledge restrictions and ineffective financial innovation policies would help them eliminate wastes in the value chain and improve productivity in their operations. This is highly interesting as current working processes don't allow for investment decisions which are based in fact. Word-of-mouth data is believed to be useful in making strategically significant decisions. Being able to make data-driven decisions would be a significant improvement in the professionalisation of business. Such a data interface would provide metrics to present to management and enable data-driven decision making. As such, this would be interesting to conscious managers in the SME manufacturing space [37].

Problem statement
Manufacturing SME's with legacy production assets have hardly any real time insight into the machine-based production process, impacting performance and flexibility.

1.4. Scope

The research in this thesis report focusses on a small section of the Industrial Internet of Things domain and aims to exploit its benefits for a specific group of companies in the manufacturing sector. These are manufacturing SMEs that use legacy production assets in production of individual components. The reasoning behind this has been briefly introduced in Section 1.3 and will be further described in Chapter 2. In Section 3.2, some recent trends in the manufacturing sectors are described. To ensure the scope is conceptually clear to the reader, the main elements are highlighted here.

The technologies mentioned in Section 3.2 can be and are readily applied in large enterprises and corporate part of the manufacturing businesses. These types of businesses have both the financial capacity and knowledge to choose future proof equipment upgrade their existing equipment. Small and medium-sized businesses frequently hold on to legacy assets, disabling from applying Industry 4.0 and IIoT innovations. These two can result in them never gaining, or losing a competitive edge in their specific business domain [26]. A model for the digital retrofitting of machines has been made, displaying the five levels of machine layers needed for digital connectivity. The physical, sensor, connectivity, data and application layer are used to identify machine readiness for digital integration. This thesis research will focus on the interaction between the data and application layer, as displayed in Figure 1.2.

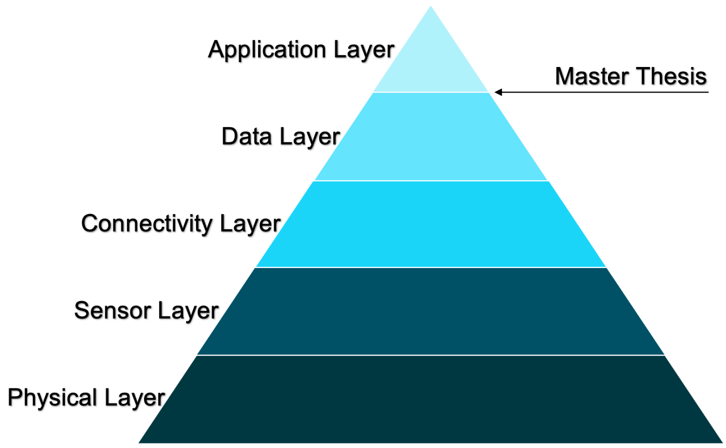

Figure 1.2: Research area, adapted from 5 machine retrofitting layers [3]

The interaction between the data and application layer would be in the form of a machine-centered data collection system with a Cyber-Physical System (CPS) integrating a Human Computer Interface. Interacting with enterprise resource planning (ERP) systems, such as pulling data and displaying results would enhance the effect the system could have on business processes. The connection to office software such as excel and outlook would primarily serve reporting purposes. The system would extract data from the machines, store this on an internal server and the actual computing would be done in the cloud, pulling data via API's onto the cloud platform. These interactions are shown in Figure 1.3.

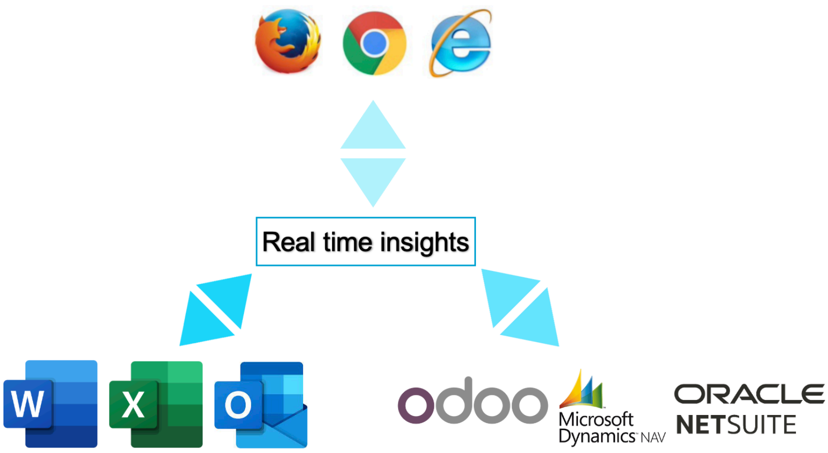

Figure 1.3: Software interactions with real time insights

The advent of the Industrial Internet of Things (IIoT) has turbocharged the rate of innovation with regards to machine connectivity and data utilization. However, the journey towards embracing IIoT technologies is not without hurdles for manufacturing SMEs. These obstacles, primarily financial and knowledge-based, hinder the integration of IIoT into their existing, legacy production systems and factories. These challenges can be overcome to enable SMEs to gain real time insights into their manufacturing operations. The industry's rate of digitization, coupled with learnings from early adopters, facilitates a gradual and economical transition. Also, data is already being generated by the large majority of machine tools, but is simply left unutilized. Challenging stakeholders to exploit this data would provide countless benefits. This thesis outlines the potential benefits, challenges, and strategies related to incorporating IIoT technologies with legacy systems. Guiding SMEs to gain real-time insights into their operations. The effect of this is production-optimization, heightened efficiency and a clear overview of the manufacturing operation. An exemplary Human-Computer Interface prototype design is created, which gives context to the roadmap and demonstrates an implementation design for SMEs integrating their individual systems. Based on these aspects related to the technology field, the main research question has been formulated: "How can manufacturing SMEs with legacy production assets enable real time into their component-based production process?'.

1.5. Structure

This thesis report will be structured as follows: Chapter 1 provides an introduction to the problem and gives context to the problem and applied industry. The scope of the thesis is laid out and a problem statement is given. Chapter 2 focuses in on the methodologies used to carry out the research into the topic. From the problem, a knowledge gap is identified. Subsequently research questions are formulated to try and solve the problem. A process is followed with a corresponding design methodology. Finally some ethical aspects of the research are considered to close out the section. Chapter 3 presents a preliminary literature review and is followed by a more extensive one to fully explore the problem and state of the art. Relevant literature streams, methods and concepts are identified and used to support the research. Chapter 4 discusses the process of doing the interviews. This begins by introducing the methods used, developing the interview guide and actually conducting the interviews. An important part in this chapter discusses the method of extracting the information from the interviews. Chapter 5 shows how the results of the interviews and state of the art analysis can be incorporate into a prototype design. Chapter 6 gives an evaluation of the prototype design and validates the prototype. In Chapter 7, the limitations of the research are discussed and the research is reflected on. Some hints towards future research are given to further the potential of the project. Chapter 8 closes out the thesis by giving a comprehensive conclusion where the research questions are answered.

2 Research methodology

This chapter will be further exploring the problem selected for this thesis research. In Chapter 1, the problem was briefly introduced and context was given to recent developments in the manufacturing sector. Now the problem is specified more to make sure a methodology to solve the problem can developed. Stakeholders are identified, with the corresponding effects the problem has on them. The value of the solved problem is visualised and explained. Following this, a knowledge gap is identified and research questions are formulated to guide the process of solving the problem. A research flow is constructed from the research questions and the process of executing the research is explored. Selecting adequate research methodology helped conceptualize goals and objectives, culminating in a project planning.

2.1. Problem

In Chapter 1, a brief problem introduction is given to provide context to the recent trends in the manufacturing sector and the current state of manufacturing SMEs operationally. There have been numerous innovations in the digitization of machines and processes. Large enterprise and corporate players have largely adopted these, enjoying a competitive advantage in the field of manufacturing compared to SMEs. Boosting output and profits alike, this has put SMEs under pressure to innovate themselves. The adoption process for these technologies doesn't appear to be effective in the context of manufacturing SMEs. The understanding of how to utilize these technologies is often absent from the knowledge base of shopfloor employees, who are usually oriented towards legacy systems. While there are established, commercial solutions available that address this issue for large corporations, their cost is a large financial barrier for SMEs, halting implementation.

Working as a manufacturing engineer in a company being geographically located far from the production facility, it has been often hard to gain access to manufacturing data in real time. There are often a lot of calls involved and time is wasted by employees who can't afford to do so. Manually retrieving machine data displaying efficiency or getting status updates on individual parts is something that takes alot of time. Employees will often get frustrated with the n-th question about production efficiency or individual parts status, resulting in negative communication and a falling out of the reporting system. Menial tasks are frustrating for everyone involved and automating them could be a big improvement. Middle management have a hard time getting the production data from the employees, as they are busy achieving their production targets. As a result, they cannot identify problems in the operation of their machines. Top level management suffers the same fate, leaving problem solutions to come too late to have an impact. If data does come through, it is often word of mouth, possible to be influenced by employees and middle management. Making decisions based on this data would seriously jeopardize the operation of the business unit or the entire company. These concerns have been visualized in Figure 2.1

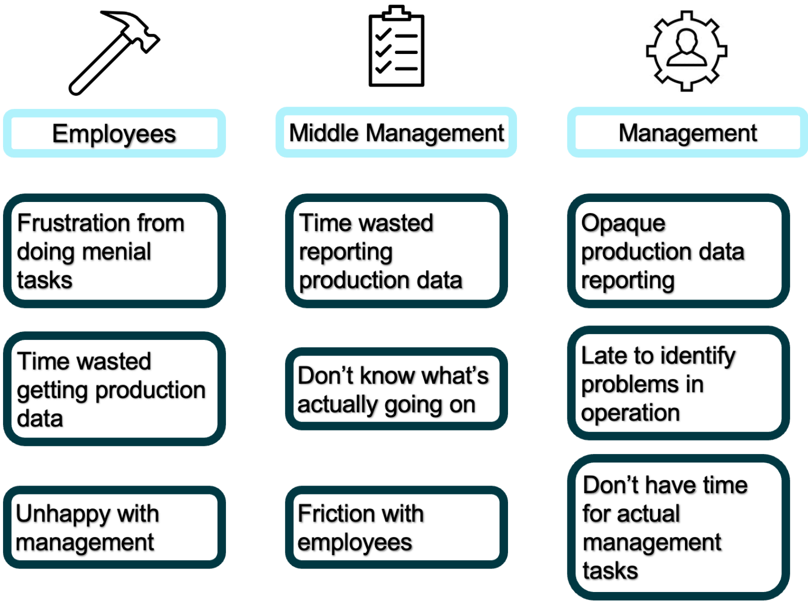

Figure 2.1: Stakeholders and the negative effects of having analog reporting of production data.

The focus of the thesis research project will be on the design of an example prototype and the plan for implementing such a system in a live environment focused on legacy assets. There have been preliminary interviews with employees and management of a company that has a geographically distanced relationship with its production facility. From these interviews, indications that the time it takes to get the data and the difference in time between getting the data and reporting is all taking too long. Such an implementation would have a radical effect on the way intra-company communication would take place and have an accelerating effect on the speed of which information is transferred between departments and management layers.

2.2. Knowledge gap

The knowledge gap is formulated from the problem statement described in Section 1.3. Additionally there is the literature research in Chapter 3, giving context to the lack of implementation of IIoT technologies in small and medium sized enterprises. The effects of not having implemented a part of these IIoT technologies (real time insights) has been visualised in Figure 2.1. Trying to create a better situation in which the different departments and management layers are able to communicate and perform together would need some kind of example for the individual SMEs. To the best of our knowledge, there is no clear roadmap available for SMEs to make this kind of step. As such, the knowledge gap based on literature and personal experience is explained in the following section:

Knowledge gap
A lack of clear implementation method on how to incorporate and gain real time insights into SME manufacturing operations.

For SMEs, it would be highly beneficial to have a kind of road map to be able to follow in order to implement and gain real time insights into their production process. Implementation would be very much easier than trying to go at the problem alone, not to mention less costly. In Figure 2.2 the factors influencing the stakeholders, their relationships and performance are indicated. The positive effects of having real time insights into their production process are as follows. Management would have an accurate and transparant overview of the data, be quick to react to production problems. They will spend less time, so can actually focus on management tasks, making their people perform at the top of their game. Middle management would have a quick way of reporting, is informed of the situation on the shop floor and will increasingly have better relations with their employees. The employees will

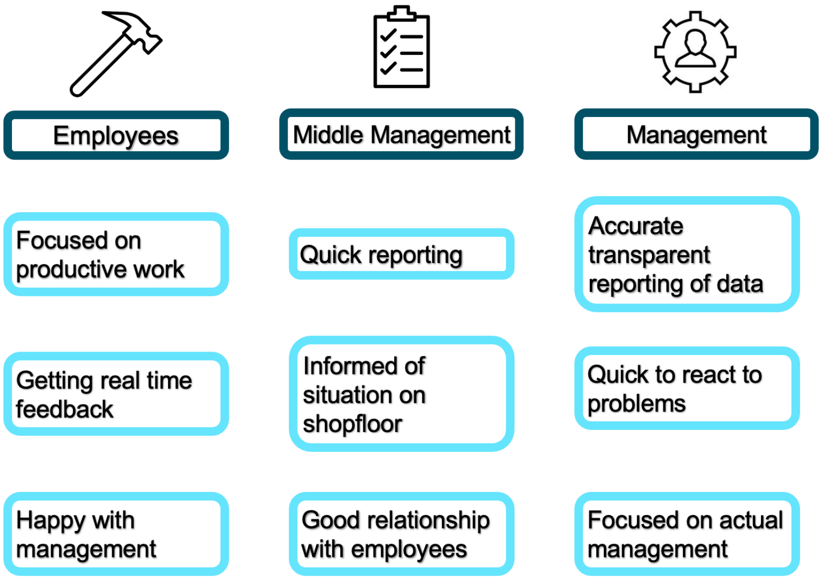

Figure 2.2: Stakeholders and the positive effects of having real time insights into their production data.

be able to focus on productive work, boosting their output. Seeing the fruits of their labour in real time can enable them to spot and sort out mistakes without management interference. A competitive environment focused on sustainable output could be a result of implementation.

2.3. Research questions

Stemming from the problem and continuing on to the research process, the following research questions are formed. The purpose of these research questions is to aim the thesis research at specific aspects of the subject in order to answer the main research question. The main question and it's sub questions are presented in Table 2.2 below.

Main Question	*How can manufacturing SMEs with legacy production assets enable real time insights into their component-based production process?*
SQ1.	What are the requirements for enabling real time insights into manufacturing SME operations?
SQ2.	What is the most crucial benefit of gaining real time production insights in manufacturing SMEs with legacy production assets?
SQ3.	What are the key features needed enabling real time insights to best serve industry professionals?
SQ4.	How do the proposed design and implementation framework improve the production process?

The main research question tries to narrow down the aim of the thesis research on small and medium-sized enterprises, which have legacy production assets (up to twenty-five years old) and are focused on component-based production. Component-based production encompasses the making of single piece production from raw material using a mechanical or computer numerical process.

2.4. Methodology

The methodology for this research was initially to make use of two proven methodologies and to adapt them into a suited method. This was to make use of the cyclical but structured methodology of the Design Science Research Methodology (DSRM) principle, but also take the application benefits of the Information System Research Framework (ISRF) into account. The DSRM process model missed some stakeholder inputs and theoretical background which are to be used in the research and the ISRF model provided a structure to implement these factors. The ISRF model missed the iterative steps of the DSRM to come to a structured process to complete the research.

After discussions with the thesis supervisors, an evaluation of the research methodology had been made. This resulted in a switch in research methodology to the User Centered Design methodology. This was because the research would not be able to contribute a significant portion towards the literature. The User Centered Design methodology is a design methodology focused on the user of the artifact being designed. It has been chosen because the thesis research focuses on the interaction between machines and humans. In this research area, the operator or end-user of the design solution is central in the design process. This resulted in the selection of user centered design. UCD and is an iterative process that looks like the ISRF and DSRM process, but is significantly more focused on iterations. The step contributing to the knowledge base is also lacking. This is more in line with the type of research and design that this thesis research encompasses. To fully understand the work that has been done in this thesis research, the procedure for completing the research has been left in this section to account for the steps taken. This includes the DSRM and ISRF adaptations, which are abandoned in the later stages of the thesis research.

2.4.1. Design Science Research Methodology

Using the frameworks of DSRM [30] and ISRF [14]: Design Science Research Methodology and Information Systems Research Framework, the research will be set up. First of using the DSRM principles as a basis on which to build the research design and adapt it into a suitable process with which the design concept is built, demonstrated and evaluated. The DSRM cycle chart (Figure 2.3) consists of six steps: problem identification and motivation, defining research objectives and solution set, design and development, demonstration, evaluation and communication. The model will initially be adapted in combination with the ISRF model to suit the research process.

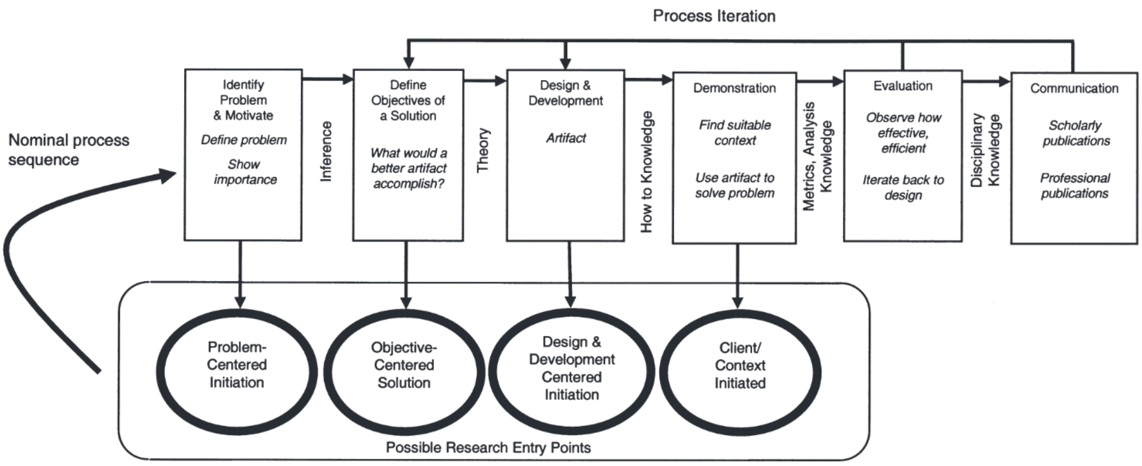

Figure 2.3: Design Science Research Methodology process model [30]

2.4.2. Information Systems Research Framework

The ISRF model (Figure 2.4) provides context to the different aspects of an information system and how it interacts with a business or research environment. It also provides context on how a development concept is based in theory and developed using theory and methodology. The framework provides guidance in how to apply a design concept in the appropriate environment and gives guidelines on how the additions in the knowledge base can be applied to develop a better concept. It uses different groups of factors: Environment, Information Systems Research and Knowledge. These are linked together by Business needs and application in the appropriate environment (Environment and IS Research). The knowledge base and IS research are linked by applicable knowledge and additions to the knowledge base.

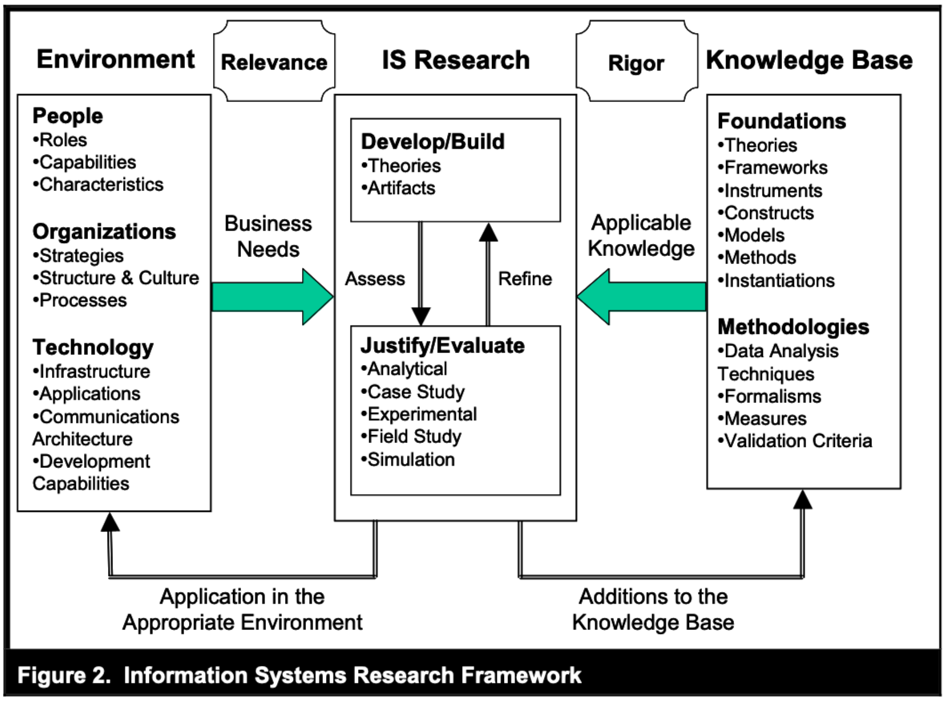

Figure 2.4: Information Systems Research Framework [14]

2.4.3. User Centered Design

The User Centered Design (UCD) framework as pictured in 2.5 is adapted from ISO9241 [16] standardizing design practices. The UCD methodology is applied to this design process, as the performance of individual machines in the production process is highly dependent on operator efficiency [4]. The operator is central in the production process, as will be discussed in a later section of this Chapter. The iterative cycle of the user centered design methodology can bee seen in Figure 2.5 and has been adapted to the purposes of this thesis research in Figure 2.7 in Chapter 5. Going through the iterative steps of UCD, first a stakeholder analysis is made to identify personas in the design context. The interaction design between the operator, manager and the system has drawn information from [10], [9] and [11]. The user persona is the projection of the target user base for which the design is made. Representing a fictional individual, assumptions regarding the behaviour of the individuals are made from literature, experience or interviews [10].

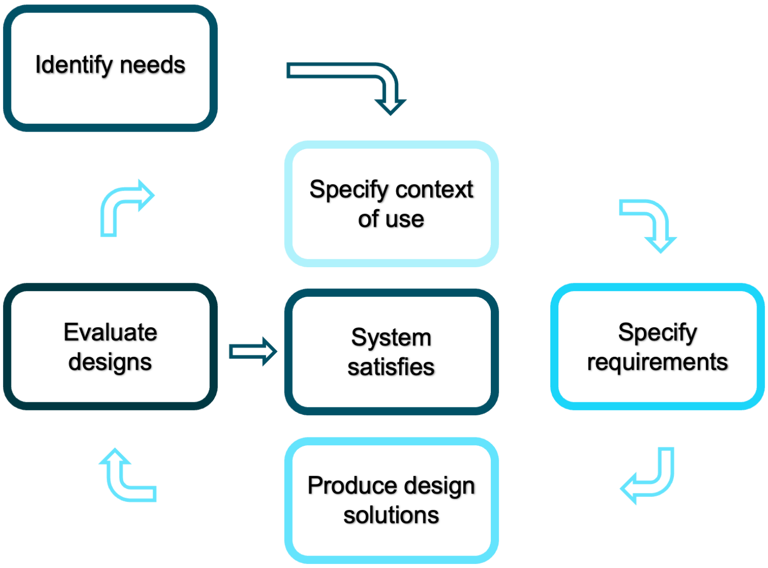

Figure 2.5: User-centered design, adapted from [16]

2.4.4. Adaptation to specific research

Implementation of DSRM and ISRF principles into the specific research methodology provides a dedicated structure to which the researcher can attach the main research question and subquestions. There are numerous overlaps between the two models. The basis would be the DSRM process model for the design of the prototype. The DSRM process model misses some stakeholder inputs and theoretical background which are to be used in the research and the ISRF model provides a structure to implement these factors. Specifically, there are factors from the ISRF model that the researcher would like to include into the research:

People Their roles, capabilities, characteristics and interactions within the application environment.

Organizations Organization strategy, structures, culture and processes.

Business needs Combining people, organizations and technology, this defines the societal needs of a concept prototype and the implementation timeline.

Applicable knowledge Methodologies and foundations for the applicable knowledge needed to structure and conceptualize a solution from theoretical background.

2.5. Application and research questions

As discussed in section 2.4.4 an adaptation between two models is made to be implemented in the specific research. In this section, the specific steps taken to come to a structured research flow are described and can be used to construct the main research question. Subquestions are then used to carve up the main question and give supporting evidence to the study. These are then the input for the research flow diagram and coupled to iterations in the research process.

2.5.1. Initial application

According to the research methodology the main research question and the subquestions are to be formulated using the steps in the DSRM cycle in combination with the ISRF. The basis for this will be the DSRM with inputs of ISRF. These steps are visualised in Figure 2.6.

The first step of the research is to identify and define the problem. The research is to be conducted from a problem-centered initiation. Identification of the problem is conducted through unstructured interviews with industry experts in the manufacturing sector. This is to understand the circumstances and background of the problem. Next a preliminary literature review on the research area of IIoT implementation in manufacturing SMEs. The domain and knowledge gap identification is a result of the literature review and can be used to explore possibilities for improvements in business processes. This implicates the relevance of the research as business needs obtained from Color Control Group are identified. Useful insights into the needs of a multinational business and its stakeholders are taken into account to shape the problem and identify weaknesses in the production process. This provides a motivation and shows the importance of the research problem.

The second step is to define research objectives and construct solution sets. Continuing on findings from the preliminary literature review, potential for resolving issues in the production process are identified and objectives for the research will begin to take shape. From recent developments in the IIoT principles and business process improvements, solutions are evaluated and weighed in the context of SME manufacturing companies. In this process legacy assets will take a central role, as this has been identified as a principal barrier in the first step of the research. An extensive literature review is key to identify these factors and delineate the problem and its solution set. From existing foundations and methodologies (ISFR) the applicable knowledge will be used to construct an environment where the eventual prototype can be evaluated to the relevant parameters.

In the third step, the design and development of a prototype is done. This will be accomplished by conducting exploratory semi-structured interviews with manufacturing industry experts. The interviews are done in a qualitative style and are tailored to the different subjects ranging from managers to shop floor operators. Exploring their views and opinions on the subject will give context to the problem and its solution set. The interviews will provide clear objectives and give evidence to constructing barriers and guidelines for implementing the prototype. Limitations of the prototype and concerns regarding implementation barriers will become clear. After these preliminary steps, a concept design of the prototype will be completed with guidance of literature in Human Computer Interfacing to focus on a core problem of the research. Presenting the information to the end user in an clear fashion.

Fourth in the research flow steps is the demonstration to the end-users. This is an iterative step in the interview process with industry experts as their feedback after the prototype demonstration will have impact on the end-result of the concept. Within Color Control Group, there is room for demonstration and experimentation using live data. This will be vital in providing evidence for the usefulness of the concept and provide business incentives to develop such a tool. Certain projects in the Color Control Group are already in development in this space and feedback from these project teams will be invaluable in evaluating the research concept.

Fifth in line is the evaluation and observation stage of the research process. Consisting of putting the prototype into the hands of end-users and implementing their feedback into the design and development stage, creates a feedback loop in which the prototype is developed iteratively. Barriers and guidelines are to be overcome and constructed to ease implementation of such a system and increase adoption of IIoT principles in other manufacturing SMEs. The evaluation is to be done by a selection of industry experts and academic professionals. This part is to be done in an interview style, where results are coded and evaluated quantitatively.

Last, the communication stage is to provide a comprehensive report, with repeatability in mind to provide scientific context and relevance to the research. Additions to the knowledge base would be ideal with possible publication. Improving upon existing foundations such as theories and frameworks with the knowledge and guidelines gained from the research. Manufacturing SMEs would have an easier time gauging their readiness for implementing IIoT principles and identify a path towards attaining and implementing process improvements. Publication of the thesis or an adapted version of it with a shortened summary could give manufacturing SMEs the practical knowledge and tools to transform their operation towards a competitive manufacturing business.

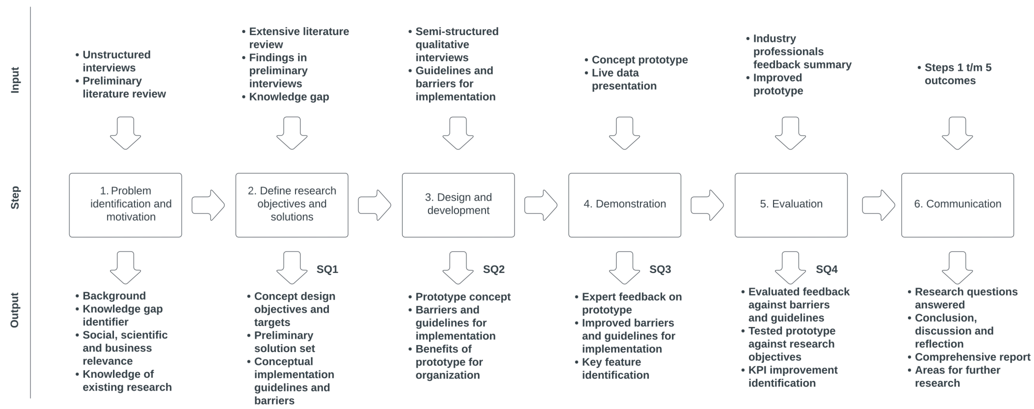

Figure 2.6: Research flow diagram

2.5.2. Final application

As a number of changes have been made to the research methodology, this section presents the final application of the research methodology. There are not many differences between the initial and final application, but they are quite important. Mainly in step three, a focus is added on the requirements of the user persona. In step six, the evaluation and validation of the design prototype weigh severely in the scientific context instead of trying to contribute to the scientific knowledge base. The design flow is presented in Figure 2.7.

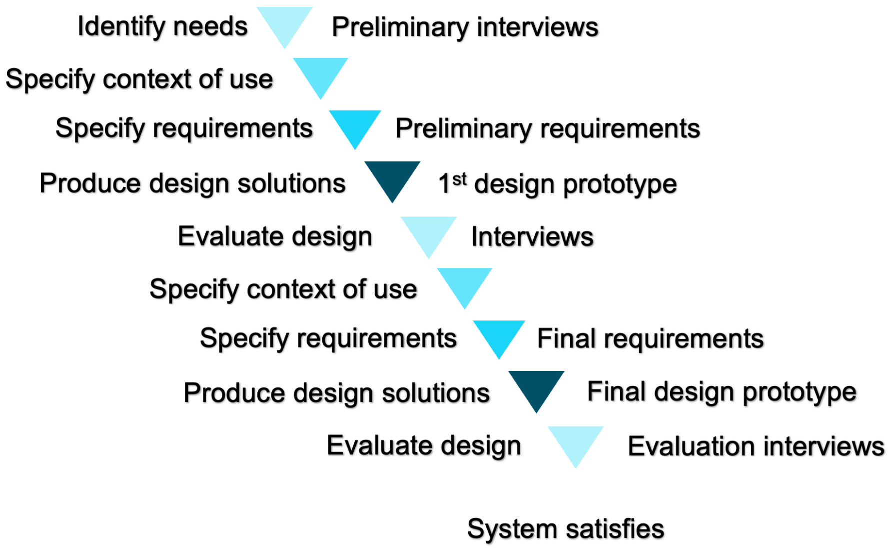

Figure 2.7: Design flow, adapted from ISO9241 [16].

2.6. Research flow

In this section, the research flow diagram is conceptualized. This gives context to the research questions and link them to specific steps in the research flow. Essentially all subquestions are important to the research, but there are some which require an individual spotlight. Subquestion 1 is important to SMEs which are not sure if they have the capability to implement IIoT initiatives. The anwer to this question will give them a grip on their situation and help identify areas for improvement before jumping into adopting these principles.

The next research question gives organizations context on what to expect from adopting these initiatives. They come with capital requirements and businesses often want to see some kind of return in the near term. Linking innovation to KPI's can give managers incentives to make strategic choices in their innovation journey.

The third research question is evaluated out of the concept demonstration and lets industry professionals give their informed opinion on the key features which have to be present in the solution set. It provides the basis for further improvement of the prototype and makes it functionally better suited to industry professionals.

The main question will be answered by combining the four subquestions into a comprehensive summary encompassing the areas of research. The evaluation stage of the research will validate the subquestions and provide a singular answer to the main question.

2.7. Interviews

In Chapter 4, Semi-structured interviews are used in this research to explore barriers and guidelines of implementing IIoT principles into manufacturing SMEs with legacy assets. These interviews are to be developed using principles, guidelines and methods from [19] and [1]. Core guidelines for developing the interviews are stated below:

- Questioning should be as neutral as possible: bias from the interviewer should be eliminated as much as possible to avoid influencing the answers of the interviewee.
- Questioning should be open: closed answers provide little value in the qualitative context of the interview and allows for freedom of input from the interviewee.

- Questions are to be worded clearly and allow for easy interpretation: using difficult nomenclature or obscure wording could confuse respondents.
- One question should be asked at a time and allow for a full answer untill moving to the next question.

In Chapter 6, the iterated concepts and guidelines are to be evaluated by a selected board of industry professionals. These interviews will take on the same semi-structured form as in Chapter 4, but are to be simplified.

Limitations to this research methodology is that using qualitative interviews, only a small section of the manufacturing industry professionals can have their say. Although this ideally minimized by interviewing from different companies, geographically only professionals from north-western Europe and eastern Europe are interviewed. North-American or Chinese professionals might have a significantly different view on these matters.

The research methodology was developed by adapting the Design Science Research Methodology [30] and the Information Systems Research Framework [14] into a research flow diagram. This was done to come to an eventual solution set and a prototype. After discussions with the thesis supervisors, an evaluation of the research methodology had been made. This resulted in a switch in research methodology to the User Centered Design methodology. This is because the research would not be able to contribute a significant portion towards the literature. The User Centered Design methodology is a design methodology focused on the user of the artifact being designed. It has been chosen because and is an iterative process that looks like the ISRF and DSRM process. The step contributing to the knowledge base however, is lacking. This is more in concert with the type of research and design that this thesis research encompasses.

3 Background

This chapter reviews the literature in fields related to gaining real time insights into small and medium sized manufacturing enterprises. It provides the groundwork for the thesis research and the design element in Chapter 5. In Chapter 2, this literature review helps build and support the knowledge gap, helping to start of the research project and giving direction to the knowledge needing exploring.

3.1. Method

After the problem has been identified, a literature review is performed to establish the background of the problem. First a few literature review methods have been evaluated and a selection has been made. The main thing to keep in mind is to know what kind of research there is to be done. In a primarily quantitative research design, the choice can be made for a systematically structured literature review such as a PRISMA style review [29]. In the case of this research, preferably a more qualitatively focused literature review is used. The methodology for this process is done in the form of a narrative review [39] where literature is reviewed in a qualitative way and interpreted by verbally describing the past studies. The focus of this method is on theories, frameworks and the outcomes of the research.

The literature areas section gives an overview of the different literature sets that are used in the development of this thesis research. The upcoming sections will focus in on a specific area of literature that is related to the larger subject of research. This section will try to explain the way these research areas are related and how they interact or counteract each other.

3.2. Sector trends

Manufacturing with traditionally labour-intensive processes have been forced in the direction of industrial automation and efficiency. Rising labour shortage, wage increases and global competition are just some of the reason manufacturing outfits have to keep innovating and optimize the human-machine collaboration [21] [20]. In this section, some core concepts and technologies are explained to give the reader context to sector trends in the manufacturing industry.

Lean manufacturing is a methodology designed to enhance process efficiency by minimizing waste within a production system, all without compromising productivity and output levels. First conceptualized by the Japanese company Toyota in their Toyota Production System [45], the methodology focuses on identifying and defining non-value-adding elements as waste. The aim is to deliver a high-quality product at a minimum cost with short throughput time by eliminating waste [45]. Though lean manufacturing employs various tools to eliminate waste and boost efficiency, the methodology itself is not a tool. Rather, it embodies a mindset and cultivates a work culture centered around continuous improvement [22].

Six Sigma is an approach striving for continuous improvement and eliminating defects in a product, process or service. Often used in conjuction with lean techniques as a means to an end, Six sigma is a data-driven methodology that focuses on process improvement and variability reduction through the execution of six sigma improvement projects [46]. The DMAIC (Define, Measure, Analyze, Improve, Control) process improvement strategy is at the center of Six Sigma. A stringent, data-driven process, supervised by team members or project leaders trained in the Six Sigma principles [31].

Machine-based manufacturing such as milling and turning outfits are trending in the direction of NC or CNC machining operations over the last decades. Manual milling and turning machines have been relegated to be back up machines or be used for quick, simple one-off parts. The CNC machines are able to make more complex parts, have significant increases in repeatability, speed, automation and cost savings [42].

Automation solutions in machine-based manufacturing have been gaining market share and penetration in the last couple of years, precisely because of the qualified labour-shortage and output requirements. In developed manufacturing economies, established players are present in the market of providing automation solutions for machine-based manufacturing operations. These market participants often provide a visualisation or data export of the realized output on their respective solutions. IIoT solutions for large manufacturers are seemingly readily available and operational[6]. These do however, require a significant amount of capital to be invested and often require new machines to be installed. Smaller manufacturing operations don't have the financial capability to procure or lack the technical knowledge to implement these solutions themselves.

A recent development in the manufacturing sector is the Industry 4.0 concept. It refers to the integration of digital processes and technologies into the supply chain and manufacturing process. When looking at the research area of Industry 4.0, [13] maps the emergence of advanced manufacturing techniques and their effects on the industry as a whole, taking into account the methodology for the implementation of these techniques. It describes their ability to gain a competitive edge over the competition when implementing these innovations. [41] describes the impact on small and medium-sized enterprises have in this emerging manufacturing innovation space. This gives an introduction on the problem that these actors are having in their respective roles. [23] gives context to the innovative approach needed to be able to implement the technological advancements. Particularly focuses on educational requirements and knowledge barriers to be overcome in the transition to Industry 4.0.

The commercialization of touchscreens has been a great improvement in the ability to integrate operator feedback and inputs into a HCI. A touchscreen can both display information and let the operator input values onto a changing display. This technology is mature and readily available for implementation. The next evolution in interface design would be an Augmented Reality Interface (ARI), but maturity and financial barriers are curbin adoption levels [5].

3.3. Review

This section is dedicated to literature review done for the thesis research project. It's focused on gaining real time insights into SME manufacturing operations relying on legacy assets. The literature review done with regards to advancements in the field of industry 4.0 is slightly different, but learnings can be gained from incorporating the material, so the researcher has cleaned up the material and it is presented in this section.

3.3.1. Purpose

This thesis research is led by the theory that data-driven decision making in small and medium-sized enterprise manufacturing investment is modern way of doing business. To achieve this ideal, practical tools to evaluate business decisions and innovations have to be developed. These tools would help SME's reap the benefits that until now only have been enjoyed by large, enterprise type operations [12]. When implementing effective innovations and lowering knowledge barriers this results in evening the playing field for these types of operations and distribute wealth and social well-being more evenly throughout society and the population. The purpose of this literature review is to provide context to the research carried out, provide a knowledge base and historical context. Also key authors in the field of industry 4.0 are identified and mentioned and the core concepts of the established literature are mentioned and their relevance explained. The state of the art in the field is briefly evaluated with a look to the future of the research field. This is done by identifying research gaps, which together with the summary come to formulate the research question.

3.3.2. Historical backdrop

When looking at the historical backdrop of the research area of industry 4.0, [13] maps the emergence of advanced manufacturing techniques and their effects on the industry as a whole, taking into account the methodology for the implementation of these techniques. It describes their ability to gain a competitive edge over the competition when implementing these innovations. [41] describes the impact on small and medium-sized enterprises have in this emerging manufacturing innovation space. This gives an introduction on the problem that these actors are having in their respective roles. [23] gives context to the innovative approach needed to be able to implement the technological advancements. Particularly focuses on educational requirements and knowledge barriers to be overcome in the transition to industry 4.0.

3.3.3. Relevant literature

Using google scholar search terms: Diffusion industry 4.0 smart manufacturing, [43] states that Industry 4.0 is on the rise in developed countries and that the integration of these technologies is occuring rapidly. The diffusion of these technologies is proceeding at a high rate of speed. Then [37] states in 'The advantages of data-driven decision making' that the organizations which are highly dependent and make use of data driven decision making are objectively better performers than 'gut' driven organizations.

In the field of Manufacturing innovations and industry 4.0, [24] argues that the benefits of the fourth industrial revolution have largely bypassed the small and medium sized enterprises. These organizations have some big challenges to overcome in order to benefit from these innovations. [36] evaluates the innovations in industry 4.0 and states that this is the present trend in automation and data exchange for industrial organizations. However, there is no generic and common understanding in terms of assessing industry 4.0 readiness in organizations. This paper provides the ingredients for evaluating industry 4.0 readiness in organizations. For the implementation of industry 4.0 [34] gives a roadmap towards implementation and some tools in order to make use of the technology. A central point taken from this paper is the notion that humans are integral in taking part transitioning towards industry 4.0 integration. The transition towards the digitization of the manufacturing operations is described by **??**. This article discusses the impact, challenges and opportunities of digitization and concludes with examples of recommended policy action. The two key instruments for enhanced value creation in the age of industry 4.0 are platform-based cooperation and dual innovation strategy.

For the integration of industry 4.0 into small and medium sized enterprises, [12] states that there are numerous challenges to be overcome in order to create digitized industrial value chains from supplier to end customer. The SMEs play an integral part in this value chain and are lagging behind in the digitization process. [15] focuses on the sustainability of the fourth industrial revolution, as it has been a serious challenge to SMEs. The Natural Resource-Based-View is the outlook of this paper. It examines the moderated mediation model of the role of information access in the sustainability of SMEs. [40] presents recent advances, current and future market trends in industrial robotics. Artificial Intelligence has evolved as the primary innovation to characterize Industry 4.0 and next-generation robotics will utilize this feature to perform collaborative tasks compared to currently deployed robotics. The current generation is still relegated to isolated work in highly controlled work environments.

In the transition from industry 3 to 4.0, [23] proposes an innovative approach with robust methodologies for strategic alignment of the technical and business components in manufacturing. An outline is given for a proposed educational infrastructure in order to address shortcomings in the education system and to better facilitate the transition to industry 4.0. In the case of [41], an investigation into 300 Industrial SMEs has been done to evaluate their adoption of Advanced Manufacturing Technologies. A new methodology for implementing leading edge technology is described in [13]. It specifies design and manufacturing companies and outlines the way for them to get a competitive advantage, supply chain integration and improve company performance.

[6] describes that a resource-based view of an organization provides the logic for hypothesizing that there will be different vertical integration patterns between companies and manufacturing operations. Early innovators are thought to have significantly higher levels of competitive performance. [33] shows that different developments over a time are indicators for raised efficiency and allow for more efficiency in the production process. This is noted to be directly responsible for the wealth and prosperity society enjoys today. [44] talks about how innovation needs to be rethought and how to revitalize the declining manufacturing sector in the United States. This is done by actively innovating, encouraging advanced manufacturing and bringing innovative technologies into the existing production processes. Finally a disruption exploration by [27] describes how large companies such as FAANG, Logitech and Ikea have been able to become succesful businesses and be responsible for disrupting entire industries.

3.3.4. Latest advancements

The literature which describes the latest advancements in the technological space of industry 4.0 and the actual implementation of innovative capacity is [15]. This article discusses the moderation of implementation of innovations particularly in SMEs. Focus is laid on the effectiveness of technical innovation. [34] explains the differences in mindset between the i3.0 and i4.0 mindsets. This article is best read subsequently to [15] because it expands on the reasons why i4.0 is not yet actively pursued by the majority of manufacturing SMEs.

3.3.5. Key authors

In the following section a couple of key authors in the field are discussed and indeed why they are found to be key is identified. Starting with [13], it fulfills the criteria as the emergence and effects of the movement are identified. [6] follows onto this research by describing a resource-based view of companies and how this impacts the diffusion of innovation. [33] is similar to [13] in providing the overview of manufacturing technology, but is more global and zooms out to earlier developments in this field. Zooming in on selected large enterprise and their implementation of industry 4.0 in their businesses [27] identifies key aspects and business-disrupting innovations. Specifically in the manufacturing space [44] calls out the American manufacturing industry to quit the 20th century and identifies factors needed for global competitiveness.

3.3.6. Core concepts and knowledge gaps

The core concepts of this literature can be found in [36]. This article indicates that there is a lack of evaluating the effectiveness of these sometimes prohibitive innovation systems. Automation is clearly identified as one of the main principles within industry 4.0, but [36] states that there seems to be a need for limits to automation in the manufacturing space. Financial mismanagement in the pursuit of ever diminishing returns indicate the need for accessible evaluation. [2] provides established data in the context of this problem. To be able to make practical use of this, an accessible tool that can actually help manufacturing SMEs make data driven business decisions is needed.

3.3.7. Conclusion

This literature review starts with the historical backdrop to the industry 4.0 revolution through the article reviews of [13], [41] and [23]. These provide an overview of the manufacturing evolution over time and give a knowledge base on which to build further research. The actual latest advancements and thoughts in the knowledge space are stated in the articles of [15] and [34]. Also the pivot is made to scope in on the space of small and medium-sized business units. Key authors are mentioned in Section 3.3.5. Core concepts such as the need for evaluation and data driven investment decisions in the industry 4.0 manufacturing revolution are given by the sources of [2] and [36]. It becomes clear that the SMEs are not yet in a position to effectively make investment decisions in this space and that there is a knowledge gap to be exploited.

3.4. State of the art

In this section the literature discussed in the previous sections is evaluated and categorized in three different domains related to the design artifact.

3.4.1. Industrial Internet of Things

The core concepts of IIoT are summarized in various work [36]. These articles indicate that there is a lack of evaluating the effectiveness of these sometimes prohibitive innovation systems. Automation is clearly identified as one of the main principles within IIoT, but [36] state that there seems to be a need for limits to automation in the manufacturing space. Financial mismanagement in the pursuit of ever diminishing returns indicate the need for accessible evaluation. [2] provides established data in the context of this problem. To be able to make practical use of this, an accessible tool that can actually help manufacturing SMEs make data driven business decisions is needed. [7] provides an analysis framework describing best practices and guidelines for designing within the IIoT domain. A resource-based analysis of manufacturing innovations related to the IIoT domain [6] with their respective competitive advantages can be used for shaping an innovation investment roadmap.

3.4.2. Small and medium sized enterprises digitization

This thesis is focused on SME manufacturing operations and their legacy assets. A review of the retrofitting process [3] provides guidelines on the retrofitting of legacy assets and enabling the application of IIoT technologies. This resource states that a non-hardware dependent solution can be implemented on legacy assets (up to 25 years old) enabling IIoT technologies [13]. Security of essential systems can be maintained by routing through existing firewall infrastructure. A resource focused on CNC machine tools [42] describes possible process innovations in the manufacturing sector resulting in efficiency gains. Cloud-based analytics and scaling interfaces across devices enable universal access to manufacturing data insights[12]. An overview of possible strategic investments [41] presents a review of possible benefits gained by implementing advance manufacturing technologies into existing production processes.

3.4.3. Human Computer Interface Design

Technological innovation does not exist on its own and is inherently part of a larger innovation system [9]. Stakeholders are vital to developing commitment to the innovation. Creating design aspects and the general idea of the design are to be adapted from [7]. The interaction design between the operator, manager and the system has drawn information from [10], [9] and [11]. The user persona is the projection of the target user base for which the design is made. Representing a fictional individual, assumptions regarding the behaviour of the individuals are made from literature, experience or interviews [10].The presentation of metrics in the design artifact is to be supported by the findings of overall equipment effectiveness (OEE) [4].

3.5. Research objectives

This research will investigate the guidelines and barriers associated with the development of a transparent real time data insights system for manufacturing SMEs with legacy assets. An implementation concept design will be presented and reflected upon. To aid adoption, guidelines will be developed during the research process to help manufacturing SMEs on the way to adopting and implementing a data solution.

3.6. Design artifact

The design will consist of an information system compatible with legacy assets in which real time manufacturing data is going to be presented to and interpreted by an manufacturing SME employee. The focus would lie on the different stakeholders which are involved with the data streams and their individual needs and wants for the human computer interface. The way information is presented to the end-user is paramount. This would be evaluated in the later design stage by way of feedback from research subjects.

This research will focus in on the needs of individual manufacturing SMEs to identify a viable candidate for implementation of IIoT data insights. The target audience consisting of operators, floor managers and business unit managers will be interviewed and their problems analysed. To model the IT infrastructure for these organisations, an implementation framework will be developed. Data processing is paramount to the overall effectiveness of the system. The implementation framework together with a non-functional prototype will be presented to industry professionals in manufacturing SME's. An evaluation will be carried out and feedback implemented. The identification of a KPI and the manner in presenting this to stakeholders would be central in the prototype. Evaluating the effectiveness of improving the overall production process with the prototype will be discussed also.

3.6.1. Semi-structured interviews

The interviews conducted in Chapter 4 will take a semi-structured form [1] and are to be inductively coded in the analysis phase. Specifying a context of use, constructing personas and requirements could be done in a quantitative way, but it is much more logical to use a qualitative analysis method. The guidelines used to construct the interviews are adapted from [19] and [1]. Relationships between these codes and the context in which they are used is analyzed with the Quantitative Analysis Guide of Leuven (QUAGOL) [8].

3.6.2. Evaluation

The evaluation of the research artifact is highly important in the process of utilizing User Centered Design in the development of a design prototype. The four iterative stages have evaluation encapsulated within the individual steps and the evaluation step is singularly dedicated to evaluation. The steps related to evaluation are described in Chapter 2 and will be described in detail in Chapters 4 and 6. The interviews in Chapter 4 are of a qualitative nature and the subsequent evaluation of the prototype design in Chapter 6 is also qualitative at its core. However, the questions asked in this qualitative evaluation are of a more structured nature and can thus be evaluated in a (although limited) quantitative manner.

4
Interviews

This chapter will focus on the method and process of conducting interviews integral to the thesis research. In Chapter 3, some preliminary, unstructured interviews were conducted with selected industry professionals. This was done to help identify the problem and to explore the research area. The interviews conducted in this section will build upon the previous information gained and focus on gaining the knowledge needed to answer research questions 1, 2 and 3. These research questions will help form a design artifact which will be described in more detail in Chapter 5.

The interviews conducted in this section will take a semi-structured form and are to be inductively coded in the analysis phase. Relationships between these codes and the context in which they are used is analyzed with the Quantitative Analysis Guide of Leuven (QUAGOL). This will unearth possible hidden requirements in the answering of the research question. First the process of conducting the interviews is explained, with all the ethical and procedural considerations described. The interview guide development is explored before getting to the analysis phase.

4.1. Interview design

Interviews are an essential step in the user centered design methodology. In order to shape the design; a context of use needs to be created as a first step. In this thesis research, before getting to this stage, an entire iterative cycle already has been completed. A context of use has already been specified, requirements constructed and a prototype design has been made. This step in the iterative design cycle serves as an evaluation of all of these aspects and tries to provide context to the end user and its needs and wishes.

Specifying a context of use, constructing personas and requirements could be done in a quantitative way, but it is much more logical to use a qualitative analysis method. The guidelines used to construct the interviews are adapted from [19] and [1]. A summary of the core guidelines for developing the interviews are stated below:

- Questioning should be as neutral as possible: bias from the interviewer should be eliminated as much as possible to avoid influencing the answers of the interviewee.
- Questioning should be open: closed answers provide little value in the qualitative context of the interview and allows for freedom of input from the interviewee.
- Questions are to be worded clearly and allow for easy interpretation: using difficult nomenclature or obscure wording could confuse respondents.
- One question should be asked at a time and allow for a full answer untill moving to the next question.

4.1.1. Language

The interviewees are selected to have the necessary English skill level required to be able to answer comprehensively. This negates the issue of them not being able to express themselves in the manner which their knowledge and experience best is utilized. The questions will be asked in English and the interviewees are expected to answer in English. If the interviewees do not fully understand the line of questioning, additional context will be provided. This requirement eliminated some interviewees from the interview. This is the main reason for the relatively few operators that were eligible for an interview. The main concepts of the interview or the questions were not clear to them and as such the interviews were omitted. For analysis and context purposes, the answers will be adapted from transcription manually and subsequently summarized by AtlasTI AI generated summaries. The summaries will be then manually adapted for missing context or containing superfluous information.

4.1.2. Preliminary interview guide

In this section the preliminary interview guide is created using the above guidelines. This interview guide is meant to be tested and adapted into a final interview guide, described further on in this chapter. The stated preliminary interview guide is not the first interview guide developed for the research project, but has been iterated upon before. The preliminary interview guide stated below is however, the first version which is tested on live subjects in order to garner feedback.

The preliminary interview guide includes findings and assumptions gained from the results of unstructured interviews conducted and described in Chapter 3. The guide consists of 9 questions, many of which allow for follow-on questions if an interesting answer is given. Indicated at each relevant question is the research question it helps to answer, giving significance to the answers and helping the researcher answer the research questions. The interview guide was made to be uniform, whatever interviewee was to be interviewed. This helps in the analysis phase, as coding structures are uniform and thus able to be compared and relations between codes identified.

Q1 To start, can you tell me a bit about your background to help me understand your perspective?

Response: Input from interviewee, can be followed with related questions and answers.

Q2 - What is your view on the company's initiatives with regards to real time monitoring of production assets?

+ Why do you see it this way?
+ What types of initiatives did you observe?
+ What are the initiatives you feel are most impactful?
+ Why are these initiatives so impactful?

Q3 - Can you describe the process of implementing real time monitoring of production assets in your company? (SQ1)

+ What were the most important requirements to enable implementing this monitoring process?
+ Why were they so important?
+ Do you think this was well executed?

Q4 - What do you see as important requirements for other companies trying to implement real time monitoring? (SQ1)

+ Why are these requirements so important?
+ If they are well implemented, what are the benefits?
+ Which stakeholders are likely to be involved?

Q5 - What are the factors which are holding back real time insights in your company? (SQ1)

+ Why is that?
+ Who can influence these barriers?

Q6 - How do you see the benefits of real time insights impacting your organization?(SQ2)

+ What is the most important benefit?
+ Why is that?
+ Which stakeholder benefits the most from this?

Q7 - What do you see as the key features of gaining real time insights? (SQ3&4)

+ Why are these so important?
+ What effect do these have on your workflow?

[Design concept is shown and explained]

Q8 - What are your impressions of this proposed design concept? - (SQ4)

+ What do you think of the division of screens between different stakeholders?
+ What do you think is the most important information on the prototype?
+ What do you think is the least important information on the prototype?
+ What are you missing in this proposed design?

Q9 - Would you like to add something to our discussion or discuss a topic related to real time insights we have not touched upon?

Response: Possible unearthing of unknown issues and solution sets.

4.1.3. Testing interview guide

As the main methodology used in this thesis research is iterative, why not apply it to the interview? The significance, validity and how fluid the interview is in practice is tested by conducting mock interviews. According to [19], a suitable way of validating interviews is to complete both expert and field testing of the interview guide. This is described in the following section.

Expert testing was done by showing and explaining the interview guide to the chair of the supervising committee of this thesis research. This feedback caused the expansion of the range of follow-on questions and the elimination of initial questions in initial versions. To see the entire evolution of the interview guide, in Appendix B this is shown.

Field testing done by testing the interview on two professional peers. The aim of this testing was to evaluate the flow of the interview guide and to identify possible awkward sequences or double questions. This caused alterations in the interview introduction and the details of conducting the interview with signing the necessary documentation and wording in these documents.

4.1.4. Final interview guide

Introduction - First I'd like to thank you for your participation in this interview. My name is Bob Warringa and I'm currently doing research to pursue my Master's degree at the Delft University of Technology. The goal of this research is to investigate how manufacturing SMEs with legacy production assets can enable real-time insights into their component based production process. This is done by conducting interviews with industry experts with different roles the relevant organizations. I am excited to be able to speak to you and hear your input on the topic at hand. Please indicate if there are any unclear questions or needs for clarification. The interview will take approximately 30 minutes.

Q1 To start, can you tell me a bit about your background to help me understand your perspective?

Response: Input from interviewee, can be followed with related questions and answers.

Q2 - What is your view on the company's initiatives with regards to real time monitoring of production assets?

+ Why do you see it this way?
+ What types of initiatives did you observe?
+ What are the initiatives you feel are most impactful?
+ Why are these initiatives so impactful?

Q3 - Can you describe the process of implementing real time monitoring of production assets in your company? (SQ1)

+ What were the most important requirements to enable implementing this monitoring process?
+ Why were they so important?
+ Do you think this was well executed?

Q4 - What do you see as important requirements for other companies trying to implement real time monitoring? (SQ1)

+ Why are these requirements so important?
+ If they are well implemented, what are the benefits?
+ Which stakeholders are likely to be involved?

Q5 - What are the factors which are holding back real time insights in your company? (SQ1)

+ Why is that?
+ Who can influence these barriers?

Q6 - How do you see the benefits of real time insights impacting your organization?(SQ2)

+ What is the most important benefit?
+ Why is that?
+ Which stakeholder benefits the most from this?

Q7 - What do you see as the key features of gaining real time insights? (SQ3&4)

- If interviewee is confused, provide examples: Spindle uptime, output visualisation, trialing performance, production planning etc.
+ Why are these so important?
+ What effect do these have on your workflow?

[Design concept is shown and explained]

Q8 - What are your impressions of this proposed design concept? - (SQ4)

+ What do you think of the division of screens between different stakeholders?
+ What do you think is the most important information on the prototype?
+ What do you think is the least important information on the prototype?
+ What are you missing in this proposed design?

Q9 - Would you like to add something to our discussion or discuss a topic related to real time insights we have not touched upon?

Response: Possible unearthing of unknown issues and solution sets.

4.2. Interviewees

For the research to have a significant value, a grounded selection of interviewees should be done. Within a specific organization, interviewees from different levels in the companies are selected. Important is that the interviewees often have interactions with each other, so the values from different stakeholders can be identified with relation to the problem at hand. The interviewees all had to be somewhat experienced with the production process within their respective company.

Selecting interviewees from different organizations and choosing them based on their work area and job activities resulted in a wide range of employees from different companies. The amount of experience with real time insights differed greatly and the level of English proficiency sometimes contrasted between candidates.

Contacting the interviewees was done through personal work experience contacts. Approval for the interviews was obtained by the interviewee or the interviewer from management. After some interviews, suggestions for new interviewees were gained from the interviewee. This resulted in useful new sources of interview data. Interviews were done in-person on location, abroad or via MS Teams. All of the interviews were recorded with MS Teams.

ID	Category	Domain	Role and job activities
D1	Director	Technical, engineering, sales	Director in a mid-sized technology company, overseeing technical development and sales engineering.
D2	Director	General management, technical	C-level director on company group level. Determining strategic goals and management KPIs.
D3	Director	Management, production engineering	General director in medium sized production enterprise. Leading a team of approximately 130 people. Setting goals and KPIs on department level.
D4	Director	Management, engineering, sales	C-level director on company group level. Determining strategic goals and management KPIs.

M1	Manager	Engineering, production	Shopfloor manager on the production floor of a medium-sized company. Leading a team of around 15 operators.
M2	Manager	Production, management	Shopfloor manager on the production floor of a medium-sized company. Is in charge of a team of around 65 operators.
M3	Manager	Quality, production engineering	Manager in the quality department of a medium-sized company. Is in charge of a team of three quality personnel. Ensures in-line quality control and the end of production quality control.
M4	Manager	Quality, production engineering	Manager in the quality department of a medium-sized company. Is in charge of a team of three quality personnel. Ensures in-line quality control and the end of production quality control.
M5	Manager	Production, operations	Manager in the production department of a medium-sized company. Leads a production team of about 10 production personnel. Is in charge of initiating production orders, ensuring progression and ultimately responsible for on-time delivery.
E1	Engineer	Engineering, automation, production	Automation engineer in a medium-sized enterprise. Implementing automation solutions into existing production processes. Updating machines to modern standards.
E2	Engineer	Engineering, automation, design	Design engineer in a small team, working design solutions for automation purposes. Producing prototypes for automation designs.
E3	Engineer	Work preparation, production	Mechanical engineer in charge of work preparation at a medium-sized company. Leading production planning, material flow, stock levels and ensuring productivity levels on the shopfloor.
E4	Engineer	Production, work preparation	Mechanical engineer, in charge of programming CNC equipment. Provides programs to the operator, optimizes production process. Selects tools and production strategies.
E5	Engineer	Design, development	Mechanical engineer, in charge of product development en product design on machine level. Producing a mechanical design, making iterative design improvements, communicating with production.
O1	Operator	Production, engineering	CNC operator of large milling machines in a medium-sized enterprise. Working one or more machines at the same time.
O2	Operator	Production	Operator in work preparation for the CNC production department in a medium-sized enterprise. Operates the automatic saw and prepares raw material for further processing.
O3	Operator	Production, engineering	Operator in the CNC department of a medium-sized company. In charge of running the machines and ensuring efficiency. Does programming of the machines and makes production reports.

Table 4.1: Overview of interviewees and their respective roles.

4.3. In practice

After inviting potential interview candidates by calling, Microsoft teams or meeting them at their desk, the interviews were conducted with the candidates who did accept the invitation. In practice, the interviews were done by creating a meeting in the TU Delft Microsoft Teams environment. All of the interviews were done in person with the meeting serving as a pleasant and secure way for recording and transcription.

4.3.1. Ethics

As there are human research subjects involved in the completion of this research, the TU Delft requires approval of the Human Resource Ethics Committee in order for the research to take place. This is done through an application consisting of three documents. First off, the HREC checklist, a general overview of the research and its objectives is described. Risks of doing research with human subjects are identified and a mitigation plan is formed through using the provided template. For the participants, the second item is the informed consent form. This document states again a short summary of the research and provides information regarding participant rights and consent information. For storing data, a DMP or Data Management Plan is submitted to the HREC. This is required to be able to store any relevant data securely and temporarily.

The audio recordings and transcriptions of the interviews are stored in accordance with the DMP to minimize data breach risks. This data will be destroyed one month after the research concludes. The excerpts, quotes, findings and summaries of the interviews will be included in the research and thus are published. Each participant of the interviews has a short summary of their interview stated in Table 4.1 and B to give some colour to the qualitative data analysed.

4.3.2. Procedure

Before the interview, the interviewee is provided with the informed consent form. This also gives the interviewee a general idea of what to expect from the interview. If the interviewee answers any of the questions with 'no', the interview will conclude there. Otherwise, all the boxes are ticked yes to provide consent. Signing the document digitally concludes this step of the process. The interviewer will reiterate that the interviewee has the right to withdraw at any moment, the interview will be recorded and that the interview will take approximately 30 minutes. A summary of the interview will also be sent to the interviewee. Getting the paperwork out of the way, the opening statement is given and the recording is started. The interview will proceed according to the prepared interview guide and clarification is given when necessary. After the interview concludes, the participant is thanked for their time and the recording is stopped. The recording and transcript of the interviews will not be indefinitely stored. The summaries of the interview transcripts and resulting analysis data will be used to extract information regarding the thesis research.

4.3.3. Data

A total of 18 interviews have been conducted in the thesis research to prepare for the design section and to help answer the main research question. Interviews are reviewed for mistakes and relevance before being admitted or otherwise. No interviews were omitted for reasons discussed in section 4.4. The audio data recorded in the interviews will be destroyed one month after the thesis research is completed, as is agreed with the participants. The transcripts and analysis results of the interviews will be kept and used for the completion of Chapter 5.

The interview data was gathered via recording in Microsoft Teams and subsequently stored in the Teams environment, before exporting to a secure Delft University of Technology cloud environment. In this secure cloud environment, for every interview subject a folder was made to store the transcript data, interview recording and the finalized transcript. To comply with the HREC guidelines and checklist, the raw recordings are not published in this thesis. The quotes, summaries, opinions are published anonymously in the Appendix B.

4.4. Analysis

In the section above, the experiments of the thesis research are described and executed. Here, the process of processing and understanding the results is described. This is done to gain an understanding of the interview data and to interpret the results in order to gain a basis for the design in Chapter 5. The answers to research questions 2 and 3 are to be extracted from the data gained in this chapter. Each transcription is read through and corrected where the AI has made an error. The transcriptions are made to be anonymous and through the AI chatbot ChatGPT summarized in 150 word summaries. Reasons for admitting an interview.

4.4.1. Methodology

After the interviews are recorded in MS Teams, the transcriptions are automatically created in the MS Teams environment. Each transcription is read through and corrected where the AI has made an error. The transcriptions are made to be anonymous and through the AI chatbot ChatGPT summarized in 150 word summaries. These 150 word summaries are used for a contextual analysis according to the QUAGOL methodology. Together with thematic coding in ATLAS TI, general findings are used to shape the design background presented in Chapter 5.

4.4.2. Key points

After assessing the results from the AI generated summaries, there was a general lack of depth detected. This resulted in a largely useless summary without any real learnings. Every transcription and recording was then combed through to create a shortened summary with only the key points described by the interviewee. This results are presented in Table 4.3.

4.4.3. Coding

The interviews are analyzed by applying thematic coding to certain quotes. This method of analysis is often applied when working with qualitative data [19] and working in the QUAGOL methodology [8]. The output of the analysis is a list of themes and interaction of themes that are identified by coding the interview transcripts. These are then identified and linked to specific quotes from interviewees. An inductive approach to the coding process is conducted, to be used with the contextual analysis. This results in general findings which are used for design purposes. The code groups categorize the codes under thematic umbrellas and are presented in Table 4.2. The individual codes have been created using ATLAS.ti software. When a specific quote was concrete enough to establish a construct, a code was created and categorized in a code group. A complete overview of the codes is stated in Appendix B, Table B.3.

ID	Name	Description
G1	Communication barriers	Codes that describe interviewee experience of hindrances in communication and information exchange.
G2	Business operations	Codes that describe interviewee experience in business operations and their opinions of these.
G3	Attention to detail	Codes that describe the interviewees view on specific aspects of the prototype.
G4	Planning	Codes that the describe interviewee views on the impact of planning on efficiency.
G5	Versatility	Codes that describe interviewee views on the versatility of a prototype and its impact.
G6	Technology	Codes that describe interviewee views on technology readiness and implementation.

Table 4.2: Code group ID, name and description.

4.4.4. Results

The interview guide has been structured in accordance with the guidelines states in [19] and [1]. This is to (as much as possible) eliminate the concerns related to participants lazily answering in a positive way. Participants involved in surveys that are too long can display this kind of behaviour and discount interview results and findings. As the participants all indicated their enthusiasm for the design prototype, this risk is minimized. Sometimes a participant needed some extra time or explanation in order to fully grasp the con and subtext of the question. Additional time for answering or explanation has been allowed in order to mitigate this risk. The results from the summaries, key points and the code relations are to be used in Chapter 5 to construct the end-user persona, workflow and requirements. These aspects are then used to come up with a final design which is also discussed in that chapter.

ID	Key points
D1	Planning of parts production would be a great addition from his perspective. Being able to track the status of individual parts allows for better communication with clients. More accurate lead times. Also an overview of bottlenecks in the production system would allow for better production planning and the ability to design for shifting of production capacity between different production systems.
D2	Production standardization is key to increasing productivity. Uniformity among processes. Complete team needs to be involved in the process improvement. Change is always hard, breaking the usual is difficult. Abrupt change is even more difficult, that's why we do continuous improvement. Visuals are important. Make sure the operator is happy. What is efficient for an individual department isn't necessarily efficient for an entire company. Context on KPIs. You'd want an aggregate variable. Parts are to be delivered just in time to reduce waste. Throughput flow is the most important. Big batches in order to get efficiency is not the way to go. We need how many per month, how much time per part, how much changeover time per part. No more stock than three months worth. Output is per machine, but operator efficiency is the most important. Planned output.
D3	Increasing production efficiency is in the participants eyes the combination of technology, knowledge and people. Real time insights could be an outcome of this reinforcing towards this goal. New equipment is always hard to get up and running. Finding out what the actual status of parts is, is a challenge. Weekly monitoring is good enough. Report in an email. Financial performance is the most important to them. Possible for finance monitoring. Wants human performance, this is the most important.
D4	Monitoring and setting KPIs would be tremendous for the business in order to improve efficiency. Current monitoring systems are more administrative. Lacking operational monitoring. Planning should be integrated in such a system. This is important in order to increase production efficiency. Context is needed in order to completely evaluate machine performance. For implementation a route of iterative improvements should be taken. Operator should have input capability.
M1	Currently monitoring machines manually. Printing out papers and displaying them on a board. Weekly monitoring. Preparing the next job would be a great feature. Program insights could lead to large efficiency gains. Tool preparation also. Shift comparisons would be great for performance review. Operator performance overview would be nice. KPI comparison is hard when provided with little context. Wants to see all of the context. Weekly and monthly reporting via email.
M2	Current systems are not real time. Need human interference. Current ERP systems are unsatisfactory for real time monitoring. Efficiency is the benefit. Management is the group who best can influence the change process. Wants to see the individuals performance, doesnt care about 24 hours. Aggregate efficiency per department is important to have. Easy reporting for use in evaluations.

M3	Quality is an important factor in this, but can only be implemented and seen after production is complete. Real time insights don't have a huge potential here. Planning is the most important aspect in this. Instructions on how the part is made need to be displayed. Feedback from design to quality and back. Quality department screen is not needed. Estimation for production time in order to improve planning.
M4	Current monitoring is through manual entering of data. Not in real time. Alot of information is going through emails at this time. Gaining real time insights is important, as you can plan for asset downtime. Planning with real time input would be great to have in order to more realistically make a production schedule. Performance comparisons between operators would be great for output and efficiency. Reporting via email or excel weekly.
M5	Weekly production insights are currently happening. Standardized communication and data would be great for reporting purposes. Real time insights would be more helpful for on-site production team, reports on production would be better for management. Effective information transfer tool would be helpful. Planning and error elimination would be helpful to improve efficiency. Top level management would benefit from a single KPI evaluating a department or factory. On-schedule production would also be of interest.
E1	Would like to see the concept being able to be generalizable throughout the production process. Tool life monitoring. Focusing on maintenance, scheduling maintenance and being able to implement this into the production planning. Operator evaluation needs to be implemented. Visualisation needs to be visible for all to see, transparency is key. Data needs to be accesssible for study of historical data. Downtime elimination results in better efficiency. More parameters would be helpful, oil, temperatures, lubrication parameters. Flexible platform. Production targets need to be visible. Maintenance screen would be helpful.
E2	Data output to the right stakeholders is lacking at this time. Nice to see for the operators how they are doing. Being able to make a comparison. Visuals are hugely important. Operator input into the system could be nice for inputting data. Planning purposes is the most crucial benefit. Seeing who or what needs to improve in order to hit targets. Company can better distribute resources and allocate funds. Making people competitive. Each machine needs to have their own display. Aggregate KPI needs to be implemented. Maintenance needs to be incorporated.
E3	Current monitoring systems are after the fact and outdated. Very high-level, no detailed status. Manual data entry is not desirable as it introduces errors or laziness. Employees will benefit the most from real time insights. Wants statistics and analysis customization. Modularity is key.
E4	Program optimization is the main focus right now. Tool library optimization for machines. Current monitoring is weekly basis. Efficiency per machine is important to have accurate information about. Legacy machines are no problem, as the data can be extracted if they are NC machines. Maintenance scheduling needs to be implemented. Measuring the stopped time is important. Flow of material, program and tools needs to be present in the concept. Emergency scheduling needs to be possible. Changeover time needs to be custom for eacht part/machine combination.
E5	No experience with monitoring systems. Feedback system to design would be nice from production. Status of individual parts is needed. Seeing how long an operation in production takes would be interesting. List of setups perhaps. Switching capacity between different production systems resulting in higher output. Parts counter would be a nice feature and batch size also. Tool life data would be great to extract from the machine. Purchasing would be interested in real time status for planning purposes. Competitiveness between different operations would be good. Real time is significant as you can solve the problem immediately.

O1	At previous companies they measured efficiency with stopwatches, manual work. Interested in the time remaining on the program in order to have simultaneous workflows. If a part has an hour of unattended runtime, this time can be spent preparing the next job, running multiple machines, maintenance or spend the break while the machine is running. Perhaps an alarm to indicate machine is nearly finished with a cycle. Currently paper results of machine efficiency are published weekly, is interested in real time insights as he believes it allows for better intervention. Tools are an important aspect to the machine efficiency. Planning would be great to see visually instead of verbally. Needs to see the tools and program ahead.
O2	The most important information to have is the planning of upcoming parts and the quantity. This helps planning for next jobs on the sawing machine. Also where they need to go. Currently gets the information verbally or via Whatsapp. For the manager it is very helpful in order to evaluate machine performance. For efficiency, needs correct information to eliminate waste. Sees a possible 30% increase in performance. Wants a display also. Transparency is important to them.
O3	Current production information is shared physically (paper) or verbally. Often rush jobs are put in between regularly planned jobs. Creating inefficiency. Financial kpi could be interesting for top level management. Finds that the time that the machine is actually running is more important than 24 hours trailing. Efficiency can be gained by having the information ready for the next job. Programmer doesn't need a screen for himself. Communication between production and design needs to be better.

Table 4.3: Interview key points.

5
Design

This section of the thesis research will focus on the design aspect of the research artifact. Using the User Centered Design method, preliminary requirements for the design are drawn up. These are formulated from the preliminary interviews conducted informally in early research phase. The requirements are influenced by preliminary desk research and literature review. Stemming from the drafted requirements, a preliminary design is made. A crude and unpolished prototype, with the purpose of demonstrating the core thinking and idea of the thesis. This prototype is to be ready for demonstration, but non-functional. After evaluative interviews, new design input is consolidated from the interview data. A more extensive literature review combined with the interview data forms the basis for the final design requirements. These requirements, together with the preliminary prototype form the basis from which the final design is developed. A further aspect of the thesis research is the key performance indicator (KPI) section displayed in the prototype. This is explored in the KPI section. After this an insight into the process of implementing such a prototype is given in the implementation framework section. Finally an example of a practical concept is provided.

5.1. Design process

In Chapter 2, some context has been given regarding the application of a particular design methodology. The User Centered Design methodology is applied to this design process, as the performance of individual machines in the production process is highly dependent on operator efficiency [4]. The operator is central in the production process, as will be discussed in a later section of this Chapter. The iterative cycle of the user centered design methodology can bee seen in Figure 5.1 and has been adapted to the purposes of this thesis research in Figure 5.2.

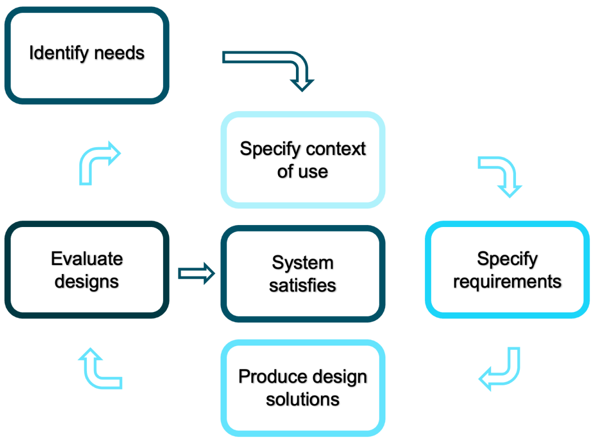

Figure 5.1: User-centered design, adapted from [16]

In Figure 5.2, the circular nature of the User-centered design philosophy has been adapted to a realized linear design procedure. This has been done with a view looking back on the design process, not visualising some design steps which are iterative in nature. For example, a linear subsequent step is made from the initial design solutions to the evaluation of the design. In reality, this was an iterative step with countless little design iterations, building towards a presentable design solution.

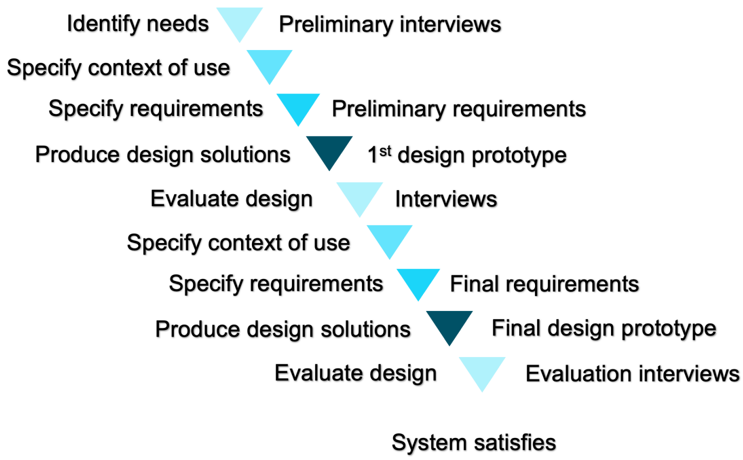

Figure 5.2: Design flow, adapted from [16]

The user persona is the projection of the target user base for which the design is made. Representing a fictional individual, assumptions regarding the behaviour of the individuals are made from literature, experience or interviews [10]. The individual needs, their desires require thinking about their environment, relations and actions. In order to get an fitting design for the individual operator, a map must be made of the operator persona. This is done through preliminary interviews and own experience in the field of manufacturing. The interactions with middle and upper management are essential to map, as these are the entities which determine targets, evaluate performance and dictate investments. In Figure 5.3, a representation of the operator persona made. Their goals are presented, in order to understand their actions and motives. These goals are very generalized in a manufacturing context within a small and medium-sized enterprise.

Figure 5.3: Operator persona and interactions with management.

To give a bit of context to the example situation for which a design prototype is made, a simplified workflow of a CNC component-based production process on the machine level is presented. This gives a global overview of the things needed to be able to realize output. Although these are just the essentials, a focus has been made on the three aspects, as the iterative process of user centered design can always expand in the later stages, but a contraction or narrowing of the scope is hard to realize after evaluation. In Figure 5.4, the workflow with only the essentials needed for production is shown.

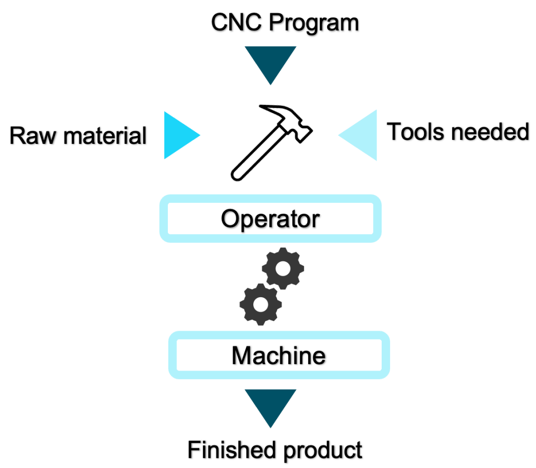

Figure 5.4: Simplified workflow in a CNC component-based manufacturing operation

Technological innovation does not operate on its own and is inherently part of a larger context [9]. The stakeholders immediately involved with the system are stated in Figure 2.2 and their interactions are explained in this section. These are the positive effects of gaining real time insights into their production process. The negative implications on the primary stakeholders of not implementing a real time insights solution is presented in Figure 2.1. These implications have been identified from preliminary interviews with operators and managers in the manufacturing sector.

5.2. Preliminary requirements and design

From experience working in the manufacturing sector and preliminary interviews with industry professionals a number of preliminary requirements have been drawn up. On the interface design side, the main resources used for creating design aspects and the general idea of the design have been adapted [7]. The interaction design between the operator, manager and the system has drawn information from [10], [9] and [11].

- **Cost** prohibitions for Small and Medium-sized enterprises looking at gaining real time insights. There are a number of ready made solutions on the market for gaining real time insights into manufacturing, but these solutions are not marketed towards SMEs and are not attainable for reasons of high costs. This outweighs the gained benefits of gaining real time insights, thus a failing business case for the implementation of such a solution is present. The companies are also not targeting the market of SMEs, as they know that there is simply little to no demand from these types of companies. Looking at marketing material of one of these companies in Figure 5.5. Their prices reflect this, as presented in Table 5.1. Only Zott would be a solution which is somewhere in the range of SMEs, but this solutions is to be classified as very basic. It translates the green signal on top of the machine, to a digital signal indicating that the machine is running. No further context is given to the machining conditions and the output.
- **Simplicity** of the data presented to the stakeholder interacting with the displayed data. The subject should be instantly informed on what the machine's current status is and whether or not the machine has been performing in the last 24 hours.

- **Lightweight** design aspects, stemming from the limited processing power cost-effective systems possess. This should result in a responsive and reliable functioning of the interface.
- **Generalizability** of the design concept across the different displays catered towards different stakeholders. If a user chooses a display not specifically catered towards them, the displayed information should be generalizable across the platform [9].
- **Visual** representation of abstract names or numbers, such as part numbers or tools needed. This enhances the subconscious recognition of the information by the operator [10].
- **Planning** of the next part to be produced for both the operator and the production manager. This has been identified in preliminary interviews to be crucial for increasing machine efficiency by letting the operator prepare the next part when the current part is running.
- **Size** of complex data displayed should be readable [9] from a 2.5 meter distance on a 40 inch display, as this is the maximum distance the operator is from a place where the display is located.

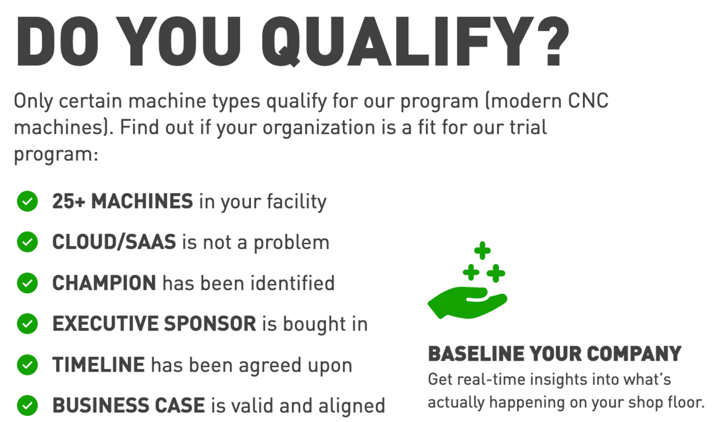

Figure 5.5: An example of real time insights marketing, targeted towards large enterprise and upscale manufacturing operations.

Name	*Cost structure*
Predator	$35.000,- implementation then $6.000,- / year
Machinemetrics	$13.000,- / year
Factoryqhiz	$9.850,- / year
Zott	$1.000,- / year

Table 5.1: Overview of ready made platforms and their respective costs.

In Figure 5.6, 5.7 and 5.8 the visual representations of the preliminary design are presented. Figure 5.6 represents the operator interface, which is located at the production asset. The connected machine is displayed, as well as the date and time. The real time insights start at the top left module of the screen, where a visual representation of the current production is located. The green background of this module means that the machine is running at full capacity at this time. The name and part number are also displayed. On the right module, a visual representation of the next part is displayed, with name and part number. This is to inform the operator what to expect as a next job. In the bottom left module, a single KPI is presented to the operator, in the form of a 24 calendar hour visual representation. 24 hours representation is the industry standard for the manufacturing industry, as there is a possibility of unmanned or outside of regular hours production. This displays the trailing 24 hours average activity overview, with the green section being full production. Red means unscheduled idle time, blue is scheduled maintenance and yellow means scheduled changeover time.

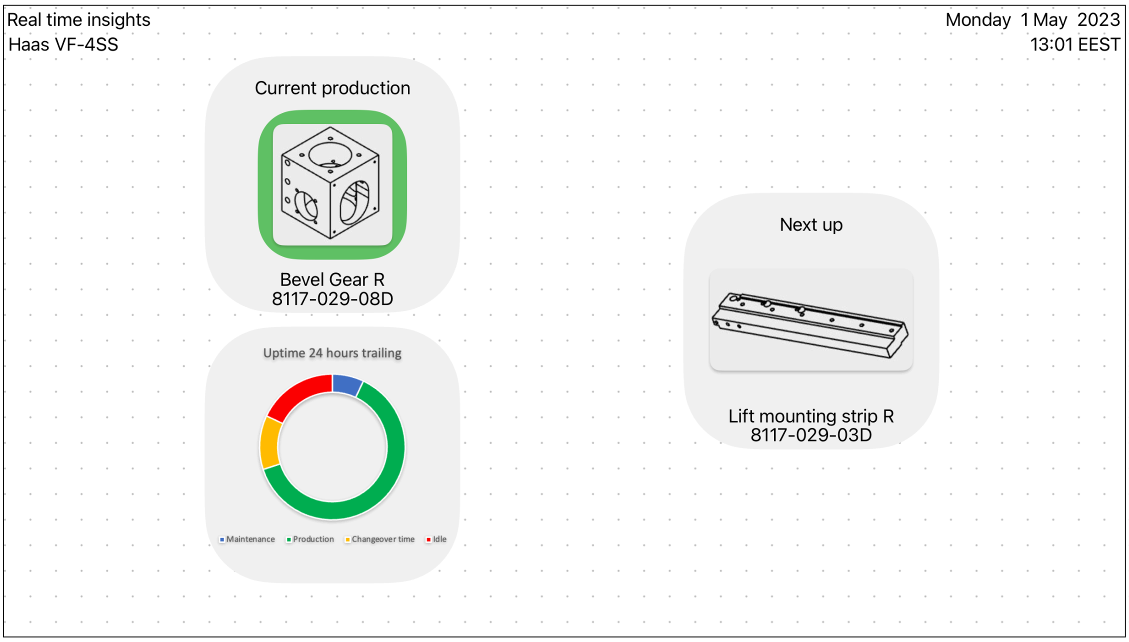

Figure 5.6: Initial design prototype, operator interface.

In Figure 5.7, the display for the shop floor manager is presented. This display is to be visible for all stakeholders in order to create transparent insights into the performance of every machine. It displays a multitude of machines in the department, overseen by the shop floor manager. The current status of the machine is presented, current production and the 24 hours trailing uptime KPI. This information is tailored to the shopfloor manager as this person is required to be on top of the current production and needs to be able to intercept mistakes in the production planning.

In Figure 5.8, the upper level management has an interface accessing real time insights into the production assets of an entire department or manufacturing operation. As the current production is not relevant and would clutter up the display, it is left out. Only the 24 hours trailing uptime KPI is displayed for every machine. This gives the upper management tailored information on fleet performance of their assets, as extracted from initial interviews. 24 hour trailing uptime can be expressed in percentage of uptime or return on capital. This is not yet implemented in this prototype, but this is custom to each individual operation and thus difficult to realize.

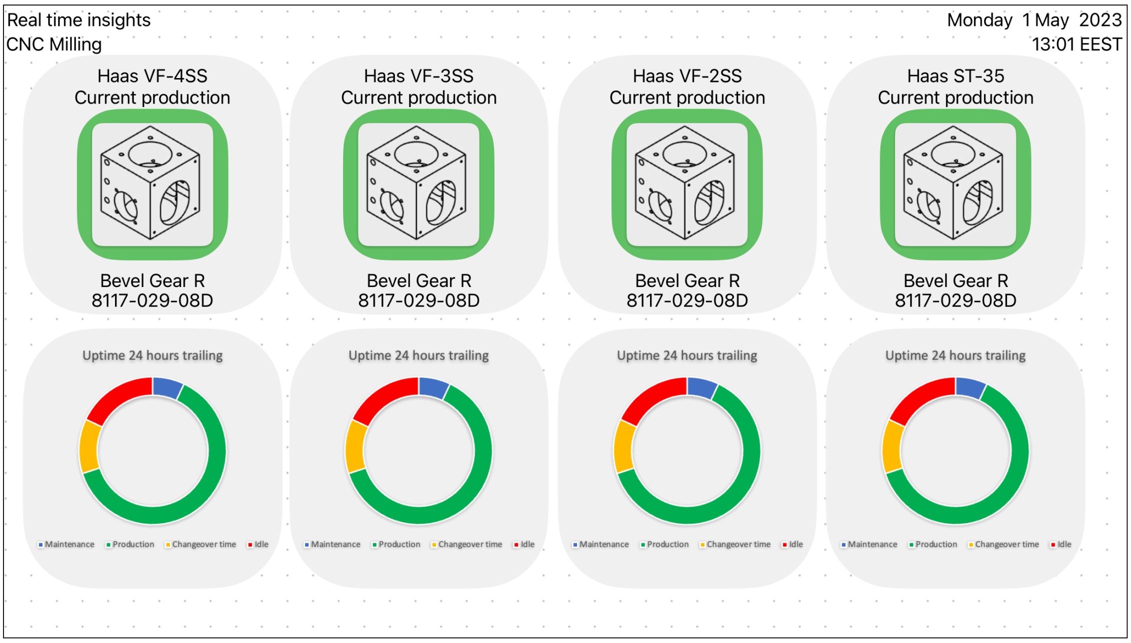

Figure 5.7: Initial design prototype, shop floor manager interface.

Figure 5.8: Initial design prototype, management interface.

5.3. Final requirements and design

In this section the findings of the interviews and literature are translated into the final requirements for the design prototype. Preliminary requirements taken from Section 5.2 are adapted and altered if necessary. From the interview data generated in Chapter 4, an emphasis was placed on the planning aspect of the manufacturing process. Key points of different interviewees indicated that a more comprehensive planning process would result in overall efficiency gains in the manufacturing process. This was backed up by the overlap in quotes of different interviewees who indicated that planning and quotes were highly related, displayed in code overlaps of production planning and efficiency. Interaction with the interface was identified as a point of improvement, as the initial prototype was not meant to be controlled by the operator at all, only displaying information. Operators indicated that they wanted to interact with the system, inputting break times or specifying reasons for downtime. This results in an increased usefulness of the data context when evaluating machine performance. It helps isolate actual problems instead of sifting through unscheduled downtime. For operators to be able to easily interact with the system, a requirement has to be set for touchscreen displays, compatible with gloves.

- **Planning** additions for the next part. This includes buttons for the needed tools, next program, raw material to be prepared, the drawing and an indication of the quantity needed.
- **Current part** information displayed, to aid personal planning. A clock counting down to the finished cycle helps the operator plan his short term activities, enabling the operator to have a higher productivity. A counter for the current series of parts needs to be included in the display as the operator can better plan the preparations for their next part.
- **Shift integration** into all of the design prototype displays. As evaluated from the interviews, shifts are the time frame that different operators are working on machines, helping differentiate between operators and evaluating shift performance. The individual operators are able to be planned on individual machines and shifts.
- **Touchscreen compatibility** of design interface, being able to control the interface with working gloves.
- **Simplicity** of data presented was evaluated to be insufficienct. The overall KPI was translated from a visual representation to a large displayed number, color coded to indicate performance levels.
- **ERP integration** of the design prototype is evaluated to be beneficial to the usefulness and minimization of manual inputs. As many manufacturing operations already use ERP systems for their individual products and stock levels, these systems can provide manufacturing data for integration into the design prototype.
- **Reporting** of manufacturing data and KPIs. The design prototype as it stands generates a wealth of real time data, lost after display and use in the OEE KPI. This data is evaluated to be highly valuable for reporting after the fact. Manufacturing data should be able to be stored on for investigation after the fact, and an automated report detailing the individual and aggregate performance should be generated by the design prototype. This is then spread via email (or other messaging service) to the relevant stakeholders in a weekly, monthly and quarterly fashion.

In the operator overview of Figure 5.9, it's clear which operator is responsible for the production asset and what shift is present at this time. This is input via the shop floor manager's interface of Figure 5.12. This is also where the shop floor manager enters the production planning of the production asset. The amount of production is also visible in Figure 5.9 and the time to completion of the next part. Then the planning interface is present on the right side, giving the operator insight in the next unique part that is on the planning. Tools, programs, drawing and raw material information is available to the operator with the press of a button. The 24 hours trailing OEE KPI is displayed with a coloured numbered interface and is able to be accessed by pressing the button. This brings the next screen: KPI context in Figure 5.10.

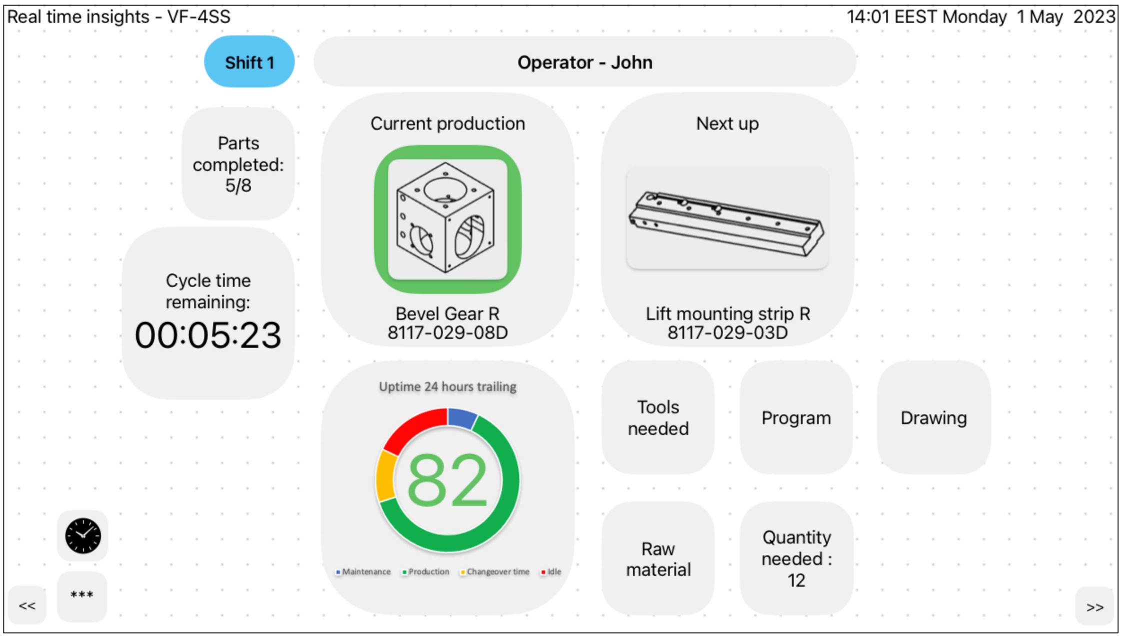

Figure 5.9: Final design prototype, operator interface.

In the KPI context screen of Figure 5.10, additional context to the trailing 24 hours of production is displayed. Through evaluating the opinions of operators, shop floor managers and upper level management, the following metrics are displayed: batch size average, number of different parts, parts quantity, 24 hours trailing performance, average cycle time, average change over time and machine power on time. These metrics have been chosen because these are evaluated as providing the basis of a situational context of the flexibility of an individual production asset.

Figure 5.10: Final design prototype, KPI context.

In Figure 5.11, the dasboard for the shop floor manager is displayed. An overview is given of the different production assets, their current production and the progress of this production. A shift overview of the operators is given to remind the shop floor manager of the operator responsible for each production asset. In Figure 5.12 the planning editing interface of each production asset is displayed, allowing the shop floor manager to make changes to the production planning on the fly, updating each operator's information and improving communication.

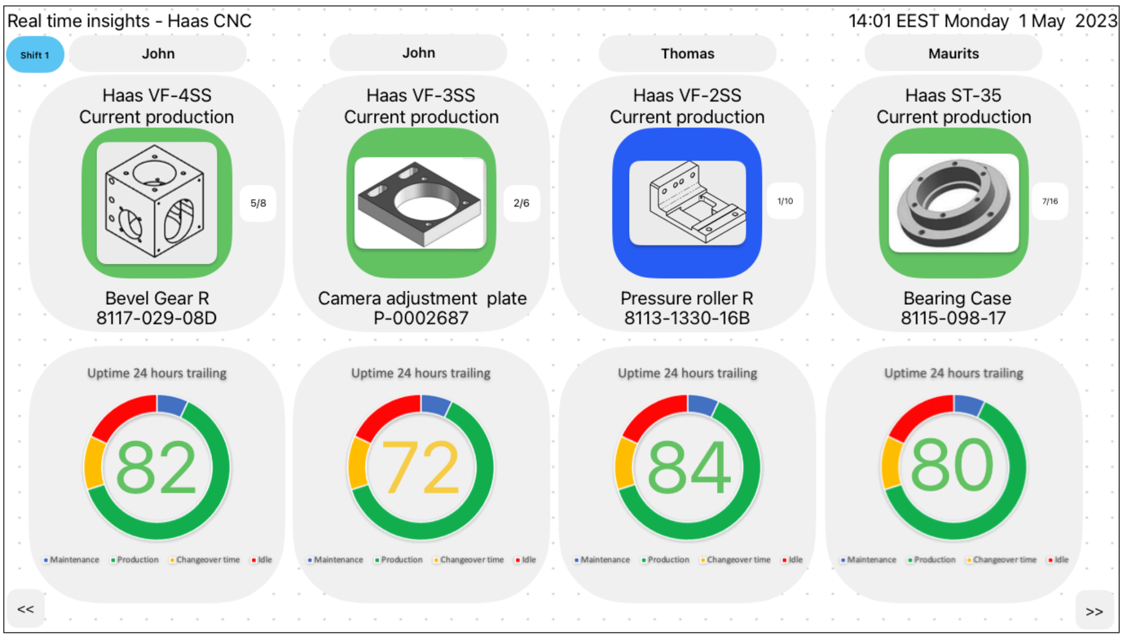

Figure 5.11: Final design prototype, Shop floor manager interface.

Figure 5.13 is accessible both by the operator of the individual production asset and the management of the manufacturing operation. This displays a simplified production planning, accounting for the different metrics, such as change over time and set up time.

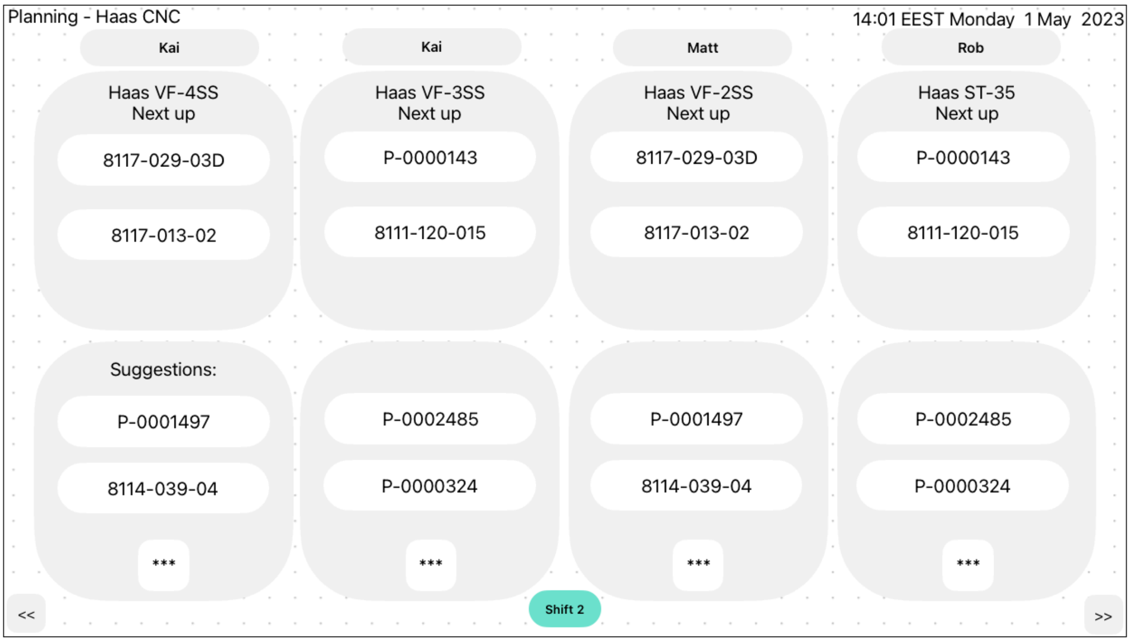

Figure 5.12: Final design prototype, Planning editing interface.

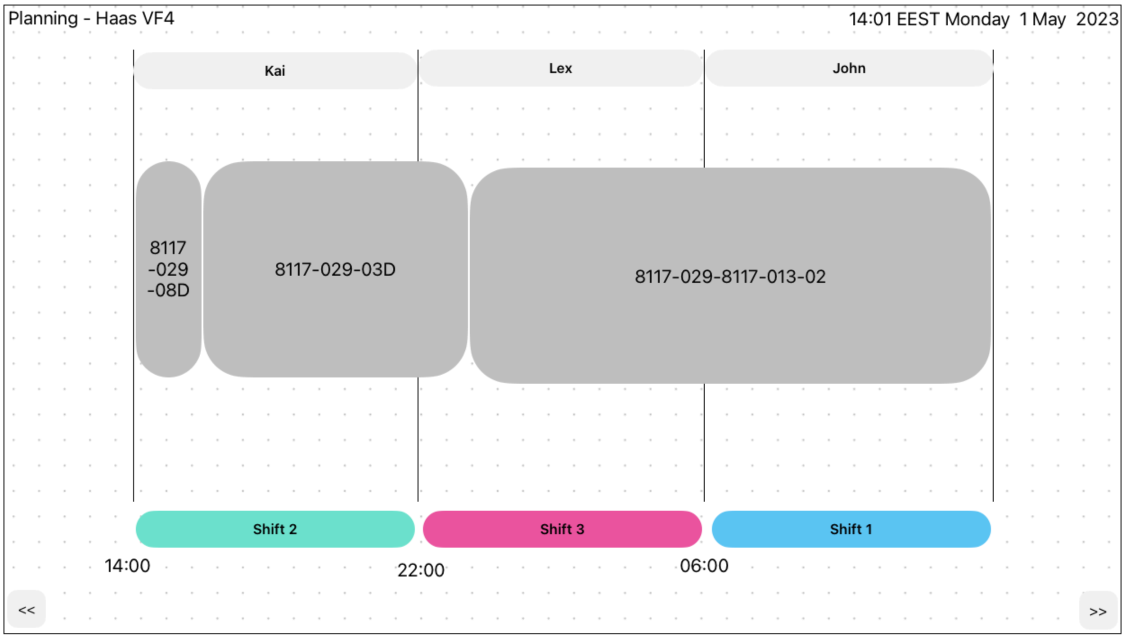

Figure 5.13: Final design prototype, Planning display interface.

Figure 5.14 provides an overview of the manufacturing operation to the top level management of the manufacturing operation. This gives real time information on the current status of the machine. It helps them initiating contact with the production floor in case of prolonged idle time. Also the 24 hour trailing OEE is displayed to give a snapshot performance summary.

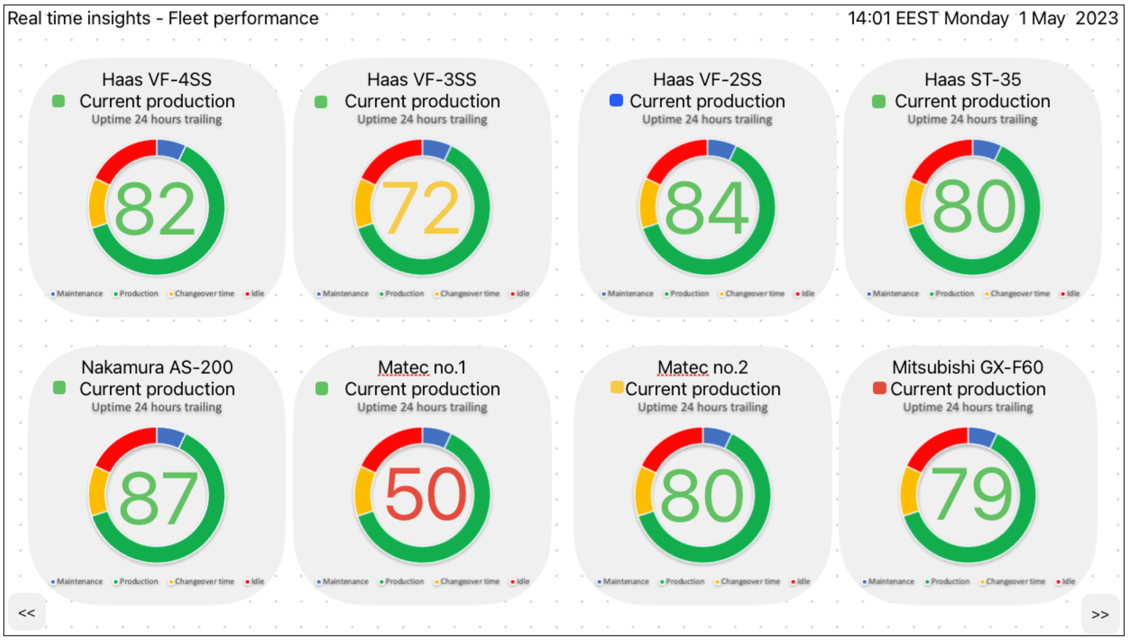

Figure 5.14: Final design prototype, management interface

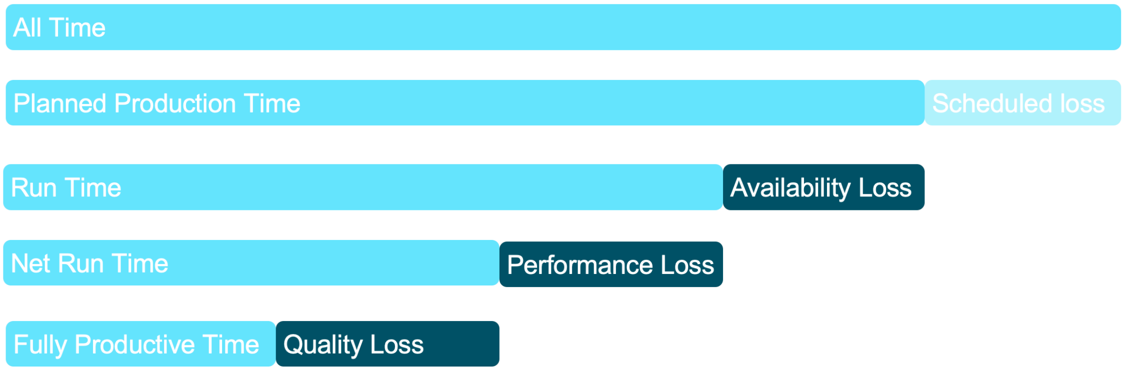

Figure 5.15: KPI development visualisation, adapted from [4].

5.3.1. KPI

In the initial design iterations only the most central key performance indicator was presented to the stakeholder, in the form of 24 hour trailing spindle up time. This was the actual time that the spindle of the production machine was moving in a CNC program, divided by a 24 hour trailing clock. In the interviews of Chapter 4 this was evaluated to be insufficient to enable real time insights. Too much of the context surrounding this KPI was lost in simplification of the design. An iteration of the interface design brought with it an iteration in KPI design. The KPI was reintroduced with the Overall Equipment Effectiveness standard of development, its development displayed in Figure 5.15. This resulted in a real time display of the Net run time OEE [4]. Scheduled, availability and performance losses are incorporated into this KPI, leaving only the quality loss to be reported after the fact. This KPI provides an accurate snapshot of the performance of individual production assets and entire manufacturing operations.

For manufacturing operations that require more context with the OEE, or have not effectively implemented the OEE standard, another display interface is developed. The 24 hours trailing display (Figure 5.10) provides the parameters of quantity of produced parts, number of different parts, average batch size, average cycle time, average changeover time and the machine power on time. These help provide context in manufacturing operations with a large portfolio of products requiring flexibility in their production.

5.3.2. Framework for implementation

In this section some guidelines for the implementation of the design prototype or an in house real time data insights solution are presented. From the interviews in Chapter 4, concerns of stakeholders were identified and learnings from succesfull implementations were translated into implementation guidelines.These guidelines will provide the implementing manager or engineer with best practices used towards successful implementation.

- **Involve employees in meetings related to real time insights and concept development.** A structured approach to developing the solution to gain real time insights needs to be presented as early as possible to employees involved in the process. The employees need to be involved and given ample opportunity to voice their opinions, concerns and ideas for the implementation of the system. This serves as a tool to generate commitment from the involved employees and ensures that the problem identified and goal is clear to the relevant employees.
- **Communicate the objectives and tentative outcomes of implementation to the involved parties.** Communicating the vision and business goals of the innovation to the relevant employees and stakeholders helps provide context to the motivation of the project 'champion'. This aids the adoption process among stakeholders and can generate useful ideas for implementation into the system. Being open for feedback is paramount in this guideline, as the input of stakeholders needs to be seriously considered to generate commitment among parties involved.
- **Methodology for evaluating performance** The increased amount of data generated can induce anxiety in employees less understanding of the project's motivation and goals. This is why a structured methodology needs to be developed in order to have transparent evaluation of the generated KPIs. This methodology needs to be understood by each stakeholder involved, requiring clear guidelines on what is to be done with the performance metrics.
- **Be flexible in information needs of employees** As every employee behaves differently in changin work circumstances, a flexible attitude from project initiators should be assumed. The employees should be given individual information, customizable to individual needs. Allowing for feedback in these informative exchanges provides a basis for employee commitment into the project.

5.3.3. Haas and Fanuc

In the CNC metal fabrication sector, over 60% of CNC controls are of Haas or Fanuc origin [17]. Actually, the Haas controllers are based on an early version of the Fanuc design and have been developed extensively since [18]. These CNC controllers are affordable, functional and are widely adopted among SMEs and enterprise manufacturing operations. In many budget oriented CNC manufacturing machines Haas and Fanuc based controllers can be found, making them a preferred choice for manufacturing SMEs. Standardizing on these systems gains them access to a pool of trained personnel and a large support network. This is why this design is tailored towards these types of controls and focuses on initial operational functionality of these systems.

Figure 5.16: An example of a widely used Fanuc control system.

5.3.4. Practical example

In a hypothetical manufacturing SME, operating legacy assets, the impotus for gaining real time insights is present. A research project has been done investigating the potential benefits of such a solution and management has agreed to go ahead with the project. Keeping the guidelines presented in Section 5.3.2, an iterative process is chosen for the development of a data extraction system. In Figure 5.17 a practical example of a data architecture solution is provided for implementation of a cloud-based processing system, accessible from anywhere on the globe (with the right credentials). For small and medium sized enterprises, which do not have the budget or the wish to access the data from the cloud, the new infrastructure section of the architecture design should be eliminated and the application can be ran on a simple laptop instead of a server.

The coding for such a data processing back-end and a simple front-end has been developed and is displayed in Appendix D. The coding language is C++ and is developed in Visual Studio Code. This code has not been tested with live data and thus can only be used as a basis to build upon.

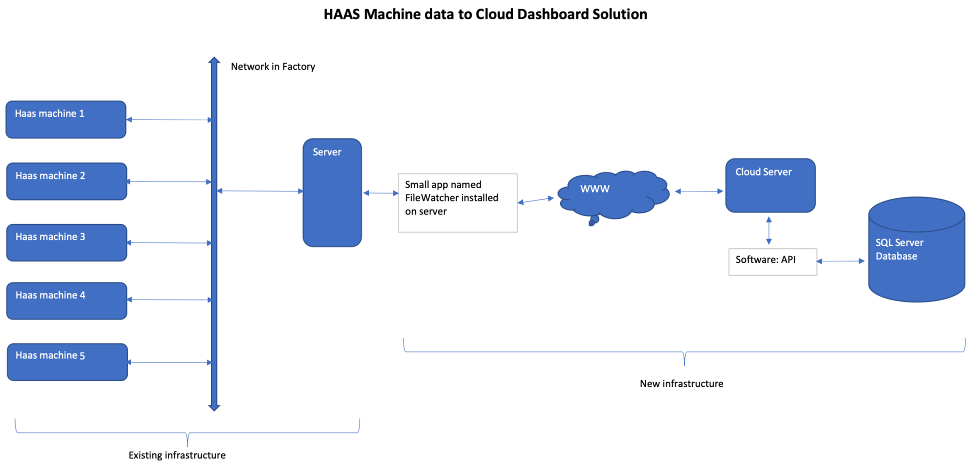

Figure 5.17: Practical example of back-end architecture in an ICT system.

5.4. Value

This chapter has described the design process from initial interviews, constructing the requirements to an evolving interface design. There have been feedback sessions and semi-structured interviews providing information and improvements to the design prototype, eventually arriving at a final set of requirements and a design prototype. A look is given into the development of key performance indicators for display on the design prototype and some guidelines for implementation are provided. Finally an example of a practical integration of real time insights is presented.

Compared to solutions tailored towards enterprise, this low-cost solution provides capabilities similar or sometimes surpasses commercially available products. This gives manufacturing SMEs real time insights into their manufacturing operations against little to no investment. Large enterprise manufacturing operations could follow their example, but scale advantages dilute the cost difference of developing their own solution.

The design, implementation requirements and example contribute value to manufacturing SMEs in providing a lightweight solution for the problems of low asset performance, low flexibility and planning. Through integrating a planning interface with operator and shop floor manager display, a clear planning can be visualised. Improved communication of changes in production planning result in a more flexible work environment on the shop floor. The real time production planning eliminates confusion and waste of production resources. Asset performance can be evaluated by professionals in every layer of the manufacturing operation and is placed into context with different variables in the KPI overview. Evaluations of these metrics can be used to identify problems and work towards solutions and a higher asset/operator performance.

6 Evaluation

The evaluation of the design prototype serves to test the validity and usefulness of the artifact and gives additional possibilities for future research. An expert panel of industry professionals from different backgrounds are presented with the design prototype, features are explained and a structured interview is executed. This chapter serves as a test for the answers constructed to the research questions answered in Chapter 5.

The design of the evaluation interviews is first explained. This provides context and its relation to the rest of the thesis research. The methodology and interview guide are next, explaining the reasoning behind questions and setting up for the next phase: analysis and results. The findings of the evaluation interviews are analyzed, explained and limitations/risks are explored.

6.1. Evaluation design

The purpose of doing evaluation interviews is to have a validating step in the design process. In user-centered design, the ever-circling nature of the iterative design process [16] uses evaluation in different forms. The choice for an expert panel semi-structured interview has been made to gain feedback from subject matter experts. This gives focused feedback and provides context to the validity of the design prototype. Due to time constraints, this evaluation is less extensive than ideal. The panel would ideally be larger to gain more information and validity. The end goal of the evaluation design is to have a satisfied system as the end state, as pictured in the center of Figure 2.5.

Evaluation interviews are setup to be in the same manner as Chapter 4. These are semi-structured interviews conducted with industry experts. However, operators are in this omitted and only subject-matter experts are involved in the evaluation. The people involved in the evaluation are in different roles: engineering, managing and direction. This gives a sound context to different opinions and validates the stakeholder commitment. The industry experts are identified as *D1*, *M1* and *E2*. These are people with different roles and places within their respective field, have different scopes and daily tasks in order to give different viewpoints on the subject. They have been already interviewed in the previous round of interviews and are knowledgeable about the context of the thesis research.

6.2. Interview Guide

The core of the evaluation cycle is a semi structured interview, which is instrumental to provide feedback. A simplified interview guide is created (relative to Chapter 4) using the same methodology as before.

The expert panel will respond to the findings of the previous interviews, presented in a visualised design prototype. The details of this prototype are explained, discussed and questions evaluating both the high-level concept and details are discussed. For analysis purposes, the interview is cut into two parts, *Q1-Q7* and *Q8-Q12* to help differentiate the different research questions.

- Show the interview participant a high level overview of the proposed design. Explain different components of the design and what they are based on.
- Show the interview participant a focused view of individual components of the prototype and the relations between the different design aspects.
- Show the interview participant how the KPI development came to be and how the different factors relate to eachother.

Q1 Do you agree with the general concept of real time insights?

Q2 Do you think the most crucial requirements are met for gaining real time insights?

Q3 Do you think that the most crucial benefit of real time insights is clear to the end-user?

Q4 Do you think that the key features needed for real time insights are present in the prototype?

Q5 Do you think the proposed design will improve the communication within a company?

Q6 Do you think the proposed design will improve the production efficiency within a company?

Q7 Do you think the proposed design will improve the productivity within a company?

Q8 Do you think the KPI development was done with the right assumptions and standards?

Q9 Do you think the central KPI gives enough context to the production process?

Q10 Do you think the central KPI gives enough information to evaluate the performance of the production process?

Q11 Do you think such a design could be implemented within a reasonable time frame in a small and medium-sized enterprise?

Q12 - Do you have any additional feedback on the prototype or the KPI development, we've not yet touched upon?

The interview starts of with a high level overview of the proposed design. After this the different design components are shown and explained why the design choices were made. After this, a more focused view of the individual components is shown and the relations between different design aspects is explained. The closed questions *Q1-Q7* are put forward and the interviewee is given time for their response and context. After this, the interview participant is shown how the KPI development was done and how the different factors related to the KPI are related to each other. Then *Q8-Q12* are posed to the participant, with *Q12* allowing for a general feedback resulting in inductive coding after the fact.

6.3. Analysis

As in 4, the responses of the interviewees are coded according to their answer. However, this round is different as they are deductively coded predating the interviews. This is to allow for a quantitative assessment after the interviews are complete. The codes range from very negative to very positive and are given a value to score quantitatively. A response is classified as negative if a respondent disagrees, doesn't see the value or otherwise reacts negatively to the statement. A response is classified as neutral if a respondent is indifferent or doesn't provide input or an opinion on the question. A response is classified as positive, if a respondent reacts positively, agrees or sees value in the statement provided. A very negative or positive code is given to statements which are in the extremes of both negative or positive responses.

Deductive coding is only used in the last question (*Q12*) to aggregate additional feedback and is done after the interviews are completed. The rest of the coding process uses pre-made inductive coding, classifying the response of the respondent in one of five possible codes per question posed. The list of codes used can be found in Appendix B.

6.4. Results

After the the analysis phase, results are tallied in this section. These describe the evaluation of the design prototype of Chapter 5. The evaluation of the design prototype, KPI and implementation is done quantitatively. The different questions are asked in a closed manner and scored numerically. In the next section, the results are presented and findings discussed.

In order to get a relative score for the individual elements, the responses to the questions were categorized in 5 different categories. Ranging from from very negative to very positive, the responses have to be categorized quantitatively in order to get a numerical value as a resulting score. The responses were coded and scored as follows:

- Very negative - **1**
- Negative - **2**
- Neutral - **3**
- Positive - **4**
- Very positive - **5**

In the right most column of the resulting Tables 6.1 and 6.2, the scores are aggregated on a scale from 1 to one hundred for simple ranking and evaluation. Keep in mind that a uniformly neutral response would result in a score amounting to sixty. In order to evaluate the negative or positive coding related to the interview, a score below 70 is considered weak; a majority of respondents are negative or neutral to the posed question.

Question	–	-	0	+	++	**Score**
Q1: General concept of real time insights	0	0	0	1	2	93
Q2: Meeting crucial requirements	0	0	0	2	1	87
Q3: Benefits of real time insights	0	0	0	1	2	93
Q4: Key features present	0	0	0	2	1	87
Q5: Improving communications	0	0	1	1	1	80
Q6: Improving production efficiency	0	0	0	3	0	80
Q7: Improving productivity	0	0	0	3	0	80

Table 6.1: Results of evaluating the concept and design.

In Table 6.1, the results of the design prototype evaluation are presented. The expert panel overall evaluated the prototype in a positive way, showing that the general concept is sound and that the benefits gained are clear to the end-user. The overall prototype met their crucial requirements for an initial implementation and were in agreement that the key features of the design prototype were present. Their understanding of what value real time insights bring to a manufacturing operation was of a high level and reflected in the score of the first question. In Q5 (improving communications), one respondent (*M1*) did not recognize the value of the design prototype. This stands out, as there is disagreement among the expert panel. Another respondent (*D1*) evaluates this as highly positive. The respondent (*M1*) indicated that the design prototype does improve information flow between managers and operators, but this information is currently transferred verbally. According to the respondent, this would result in a cancelling out of communications improvement.

The expert panel agreed that, if implemented, the design prototype would result in improved production efficiency and improved productivity. Together with the zoomed out general concept and benefit identification scores, the validation of the design prototype by the expert panel is completed.

Question	–	-	0	+	++	**Score**
Q8: KPI development	0	0	1	2	0	73
Q9: KPI context	0	0	1	1	1	80
Q10: KPI evaluation	0	0	1	2	0	73
Q11: Implementation of prototype	0	0	0	2	1	87

Table 6.2: Results of evaluating the indicators and implementation.

Table 6.2 gives the results of the second part of the evaluation. The scores here are significantly lower compared to the first part of the evaluation, especially in the context of KPI development and the evaluative capability of the central KPI. The contextual descriptive capabilities of the KPI scores a little higher, but also scores a neutral evaluation from one respondent. The conclusion can be drawn from this data: the presented key performance indicator needs some further work. One respondent (*D1*) indicated that the development of the KPI could not be considered to be correct in following standards and guidelines. This was because the OEE was to be considered in the context of an aggregate number, not only the singular asset. The assets are to be evaluated together with their human operators in order to get an effective and useful number. Another respondent (*M1*) evaluated that the KPI context was not extensive enough. They considered that the operator efficiency was not displayed, which would enable comparisons between operators in different shifts or machines. This would add value in the managerial role of evaluating operators, correcting behaviour and retraining. The evaluating capability of the central KPI was considered to be neutral by a respondent (*E2*). According to the respondent, there is not enough information to completely evaluate the performance of the production process, as the interface is focused on individual assets. The respondent would like to see a more aggregate KPI in order to be able to evaluate the entire chain of production, from raw material to finished product.

The expert panel's answers to the last question *(CE50-55)* indicates an overwhelmingly positive response as the respondents all believed that such a system could be implemented in a reasonable timeframe (less than one year) in their respective environments. The experts believed that this is a process improvement that is technically and financially feasible. With their previous statements and opinions regarding the overall soundness of the design concept in mind, the question of: 'Why this has not been implemented yet?' surfaces. This can be brought back to the concept that being able to do something, does not mean that the awareness of the need is present. Thus, nothing happens. The respondents all indicated that, presented with a possible solution for a machine data interface inspired them to initiate projects and research possibilities for implementation.

The inductively created code *CE56* indicates that the respondent (*M1*) finds it important that the KPIs are different per machine and need to be evaluated individually in order to have display effective evaluations. This might be impossible to implement as there needs to be knowledge of every individual machine in order to have a tailored solution. As there are countless designs and implementations of machines used by small and medium sized enterprises, this is considered to be impossible to be implemented in a general solution or design concept.

The results of the evaluation are overall quite positive, leading to concerns regarding the significance and validity of the above stated findings. The interview has been structured in accordance with the guidelines states in [19] and [1]. This is to (as much as possible) eliminate the concerns related to participants lazily answering in a positive way. Participants involved in surveys that are too long can display this kind of behaviour and discount interview results and findings. As the participants all indicated their enthusiasm for the design prototype, this risk is minimized. Sometimes a participant needed some extra time or explanation in order to fully grasp the con and subtext of the question. Additional time for answering or explanation has been allowed in order to mitigate this risk.

The consensus is that the ability of having objective transparent insights into the manufacturing data leads to increased production efficiency. This benefit is gained by the increased capacity to identify problems, evaluate production processes and implement process improvements. A further benefit stemming from the gain of real time insights is the improvement of communication, eliminating misunderstandings in production orders and production status.

The positive results of (especially) the first part of the interview could be caused by the phenomenon of being blinded by the supposed benefits of a new innovation, resulting in overwhelming positive responses and negating any potential pitfalls. This has been mitigated as the respondents have been quite critical in the second part of the interview, giving context to their understanding of the design prototype and the pitfalls that can be identified. This gives the evaluation validity and reinforces positive outcomes. The results show that the design prototype is a feasible and useful artifact, but there is future research yet to be done in order to fully explore the capabilities of the design concept.

7 Discussion & Recommendations

This section discusses the findings presented in this research. The research limitations surrounding the design prototype will be evaluated, since these are important to keep in mind when assessing the quality of the research prototype and determining whether it can be implemented. Furthermore, a personal reflection on the thesis research is conducted to evaluate sections of the research and place the work into personal context. Finally, the limitations of the thesis research are used for suggestions for future research to be conducted in continuation of this research project.

7.1. Research Limitations

This part of the discussion will discuss the research limitations encountered during the research and design project. The scope of the research project focuses on small and medium sized enterprises with legacy assets, so the limitations are related to the boundaries of the scope as well. In the last part of this chapter, views are given on how some limitations can be marginalized through further work in the research area. When evaluating the limitations, a number can be attributed to the limited time available for the research project, but with further research could be developed into viable artifacts.

- **Non-functional design prototype:** The developed design prototype was presented in a non-interactive way. Encountered time limitations made it impossible to develop a functioning prototype for interacting with the interviewees. A proof-of-principle functional code is presented in Appendix D, but this was not ready in time for the initial interview rounds and evaluating the design prototype. As a major part of the design prototype is the interaction of the human and the touchscreen interface, ideally there would have been a testing phase where the subject could actually test the functionality in a production environment.
- **Testing limitation:** The testing of the design prototype was done in an interview style, where the interviewee was situated in an environment not representative of the actual production environment. To obtain a good sense of the necessary features and clarity of some visual aspects of the prototype, the testing of the design prototype should have been in an environment more representative of a manufacturing operation. The design prototype should have been tested in a setting more representative to a manufacturing operation to obtain a good understanding of the necessary features and clarity of some visual characteristics that should be included in the prototype.
- **Operator efficiency:** From the second round of interviews, a general feedback point of most interviewees was the fact that there was not enough emphasis on operator efficiency. In this thesis research, emphasis is placed on machine efficiency, but many interview subjects and stakeholders have presented their interest in evaluating operator efficiency together with machine efficiency. This creates a more complete view of the manufacturing operation and pinpoint areas for problem identification, innovation and process improvements. The operator element could be used to identify star-operators in the production value chain and encourage them to transfer their knowledge to under-performing operators.

- **Research is limited to manufacturing sector:** This research only focuses on the manufacturing sector. This is quite a specialized business sector and findings of this research may not be applicable in other domains. The main focus of the manufacturing sector is the interaction between human and machine, identifying inefficiencies and minimizing these inefficiencies by means of implementing process improvements. The machine element is a quite unique element of this sector, as there is a lot of specialized knowledge required to operate complex manufacturing equipment. Furthermore, experience and teamwork is required to efficiently run an operation.
- **Component-based production focus:** Within the manufacturing sector, the component-based manufacturing in CNC machines is quite a small part of the entire value chain of product manufacturing. This sector often treats these small, individual products as the centre-piece for their operations. Therefore, knowledge obtained in this research may not be applicable in other manufacturing sectors, such as process-based mass manufacturing or the boutique individual custom made manufacturing operations. The use of largely computerized machines is prevalent in component-based manufacturing and the data generating capabilities of these machines is largely standard within the industry, making the research quite focused on the component-based production process.
- **Small and medium-sized enterprises (SME):** This thesis research is targeted towards SMEs, which have their individual guidelines and barriers (financial and knowledge barriers, importance of employee commitment). As this research is conducted with these barriers and guidelines in mind, generalizability in the entire range of companies is not possible without further investigation in the other company profiles. This research may not be representative for implementation of real time insights in large manufacturing operations, but with integration of existing systems in the corporate sector it could be a viable cost-effective solution.
- **Legacy assets:** The implementation framework and prototype design are focused on legacy assets which itself don't have smart processing implemented in the machines. Newer machines do have integrated processing and data visualization techniques. Therefore, the research may not be relevant to these newer machines. The design prototype might not be viable for integration in these kind of solutions. **Professional bias:** This research has been conducted from the viewpoint of a manufacturing engineer, focused on the performance of human and machine production assets. Together with the selection of interviewees being industry professionals, a quite narrow viewpoint is presented. This needs to be taken into account when evaluating the thesis research.
- **Maintenance:** The research does not account for the maintenance of the machines. However, these are vital to the production process and its efficiency. The interviews showed there was a high demand for incorporation of this factor. More information about maintenance provides a baseline for higher uptime of machines and thus increased output performance.

7.2. Reflection

This section serves to look back on the research and discuss some findings and reflect on them. This research project began as a curiosity from personal experience to look into how organizations as a whole as well as individuals could best be presented with manufacturing data. How can people use the data that the manufacturing operation generates, and what are the benefits to be gained by making use of this resource. Looking further, a sense of urgency in implementing this kind of solution was detected, by comparing SMEs with large enterprise. These operations usually already have adopted some kind of data system in their manufacturing operation and are reaping the benefits of this, creating a kind of gap between different size enterprises. When further investigating this issue in the component-based manufacturing sector, an opportunity was identified for small and medium-sized enterprises. The technology for generating data is often already present in legacy machinery (up to 25 years) and the data can be extracted and presented to the right stakeholder. Usually there is no significant investment required to safely link the legacy assets in a networked environment to create a localized data display. Obtaining cloud-based access to the data requires additional costs for server provides, but these costs are nowhere comparable to ready-made solutions from commercial real-time insights vendors. This placed the research focus largely between the data and application layer of retrofitting manufacturing operations. The design prototype created and the example framework for implementation can serve as a template for ambitious manufacturing SMEs looking for affordable digitization. Feedback from the exploratory interviews and evaluation interviews indicate that there is a high level of curiosity among managers, engineers and operators alike for this kind of innovation in the manufacturing operation.

To do research in this area provided an interesting challenge as it was difficult to get started and gather the scope of the research. Personal connections through professional contacts proved highly valuable in order to conduct interviews. Overall the enthusiasm for the interviews was high, with willing participants.

Designing the framework and prototype proved to be a challenge as there were significant changes in the research methodology. These proved to be very time consuming, creating a challenge in the research time frame. This ate into the additional features of the design and testing phase.

From the different rounds of interviews, a surprising finding was the importance placed on production planning. This was a feature that had to be implemented, otherwise invalidating the benefits of the prototype. This could be organization specific, but the general impression was otherwise. Another surprise was the enthusiasm for a competitive element in the display of data. The operators specifically really wanted to see them compared to their peers and vice versa.

Before the start of the research and selecting the methodology, the part of conducting the interviews was a very daunting concept. In contrary, conducting the interviews was a very pleasant experience and proved very valuable for the research. The interviewees largely showed great enthusiasm for innovation in their respective professional domains and were motivated to provide input for the thesis research. Overall a pleasant experience.

7.3. Recommendations for further research

Potential future research objectives in the area of gaining real time insights into manufacturing operations are obtained by evaluating the research limitations and reflection sections. The overwhelming majority of interviewees indicated the importance of advancements in this field and expressed their curiosity about future results. This could indicate a demand for the design prototype and its functional descendants. A short summary of further research to be conducted is stated below.

- **Functional prototype:** The next step is to develop a functional prototype with a physical interface in a live-data production setting. Bringing operators, managers and engineering staff in contact with a functional prototype will help finally validate the features and design aspects of the design prototype and provide valuable feedback for further development. This would also serve as a catalyst for gaining commitment from stakeholders in the form of investment aimed at developing a functional product.
- **Helping engineers develop:** The research aids engineers in the development of similar tools in gaining real time insights by providing an example framework and interface design. The next step could be the development of a manual, aiding developers and engineers in realizing real time insights into their manufacturing operation.
- **Operator performance:** From the limitations section and the aggregate interviews, it's clear that the operator performance metric is something that is currently missing in the design prototype and would be greatly appreciated by design stakeholders. Researching how this metric could be presented and evaluated would be an interesting proposition as there are many factors involved with the human element of manufacturing efficiency.
- **Expanding applicability:** The current implementation prototype is focused on Haas machines and Fanuc based controls. From this research, it is concluded that these kind of machines are most prevalent in SME manufacturing operations, but there are countless other brands in CNC milling and turning. Another possibility of expanding the applicability of the design prototype would be by adding other machines in the component-based production process. Sawing, grinding and welding stations could be implemented as part of the production process and be a useful addition to the context of the manufacturing operation. Further research would benefit the managers and operators with these kind of assets in evaluating their performance and gaining insights into the manufacturing operation.
- **Aggregate evaluation:** Particular interviewees, mainly in the management target audience, indicated that evaluating individual machines is a nice development, but to really understand oper-

ational efficiency an aggregate KPI needs to be an output of the system. This can then be used to set targets for an entire organization and to gauge how the entire operation is performing at any time. Further research is needed that focuses how this KPI could be best composed and presented to the target stakeholders.

- **Customizability:** In the current design prototype, static displays are used to present data to the stakeholders. In the interviews, there were numerous requests to add or remove metrics. To account for individual user demands, being able to customize and make individual changes to the interface would be beneficial to create employee commitment to displaying data. Research needs to be done on how to best offer customization options to individuals, keeping the central concept of the designer in mind.
- **Production planning:** The design prototype was updated after the second round of interviews with the addition of a planning module, as the interviewees indicated that a forward looking planning module was crucial to improve communication and efficiency. Further research is needed on the presentation of production planning and the feedback into the production planning system based on manufacturing data.
- **Integration with ERP system:** Modern companies cannot do without Enterprise Resource Planning (ERP) systems. Manufacturing companies use these systems to run their factories operationally and administratively. Integration of the real time insights system into an ERP solution would greatly benefit the usefulness of both systems. Further research needs to be done in this area: how to integrate machine-based systems and resource-based systems in order to create synergies in manufacturing operations?
- **Complete KPI integration:** The current evaluative tool, OEE, does not completely consider the production chain. The quality element is not considered in the evaluation of the production chain and thus it does not represent the complete definition of the OEE KPI. Further research into the integration of the quality element into the evaluation system needs to be conducted in order to solve this.
- **Universal implementation:** Currently, the design prototype system focuses on component-based manufacturing solutions. This is a hard limitation on the applicability of the system, which could potentially also be used for process-based production of mass manufactured goods. Further research needs to be done on how to represent the performance of these production processes.
- **Maintenance:** Currently, the system does not take maintenance into account. This is a vital part of running an efficient manufacturing operation and there have been numerous publications on the process of preventative maintenance. Further research should be done on how to combine the manufacturing data and the preventative maintenance infrastructure into a system which can integrate these factors for an accurate forward-looking production planning.
- **AI customization:** The system as designed is a quite static representation of the machine data. With recent developments in artificial intelligence, it doesn't take much imagination to consider the advantages this could have on the representation of data by AI integration. Further research needs to be done on how to securely integrate artificial intelligence in order to better present data and recognize manufacturing data patterns.

8 Conclusion

This chapter considers the key outcomes from the prototype design and the findings from the evaluation interviews to form the answers to the four research questions. First the focus of the thesis research is reiterated. Following this the research questions are answered, a mention is made of the developed KPI and the relevance of the research is explained.

Working as a manufacturing engineer in a company being geographically located far from the production facility, it has been often hard to gain access to manufacturing data in real time. There are often a lot of calls involved and time is wasted by employees who can't afford to do so. Manually retrieving machine data displaying efficiency or getting status updates on individual parts is something that takes a lot of time. Employees get frustrated with the n-th question about production efficiency or individual parts status, resulting in negative communication and a falling out of the reporting system. Menial tasks are frustrating for everyone involved and automating them could be a big improvement. Middle management have a hard time getting the production data from the employees, as they are busy achieving their production targets. As a result, they cannot identify problems in the operation of their machines. Top level management suffers the same fate, leaving problem solutions to come too late to have an impact. If data does come through, it is often word of mouth, possible to be influenced by employees and middle management. Making decisions based on this data would seriously jeopardise the operation of the business unit or the entire company. *Manufacturing SMEs with legacy production assets have hardly any insights into the machine-based production process, impacting performance and flexibility*

This thesis research is focused on the area between the application and data layer of manufacturing digitization [3]. The interaction between these layers and the presentation of the data to the relevant stakeholder is described in the next section. Primarily, the four research questions are answered before assembling these questions into the main research question.

Research question 1: *What are the requirements for enabling real time insights into manufacturing SME operations?*

In Chapter 5 the requirements for a design prototype of a real time insights solution are developed with the input of literature and the interviews in Chapter 3 and 4. A design solution with in house developed infrastructure can be enough to gain real time insights into the manufacturing operations. The scale of SMEs requires this needs to be a lightweight design with a minimal amount of features and design elements. Often real time insights can be enabled through existing data generation of the machines, as these are capable (up to a certain point) of extracting data from the production process. The challenge then is to present this to the relevant target audience. This has been described in Chapter 5. Some specific requirements related to the human element of implementing such a solution are found in the evaluation stage of the design. The commitment of people working with the system is of paramount importance, as these stakeholders can make or break the implementation of a system. Their willingness to change needs to be present in order to make use of the benefits resulting from system implementation. Of course, the technology base needs to be there, with legacy systems up to 25 year being able to generate the data. Then the technological requirements are flexible, when implementing a cloud-based processing platform they are quite a bit more extensive than just a computing solution. The main requirement for manufacturing SMEs is a transparent culture, the willingness to let the data do the talking instead of subjective opinions. If this is realized, the hunger for increasingly more useful insights will be present in all stakeholders.

Research question 2: *What is the most crucial benefit of gaining real time production insights in manufacturing SMEs with legacy production assets?*

The most crucial benefit of gaining real time insights in the production process has been evaluated among industry professionals, managers and the expert panel in Chapter 4 and 6. The consensus is that the ability of having objective transparent insights into the manufacturing data leads to increased production efficiency. This benefit is gained by the increased capacity to identify problems, evaluate production processes and implement process improvements. A further benefit stemming from the gain of real time insights is the improvement of communication, eliminating misunderstandings in production orders and production status. Employees are now informed about their efficiency and upcoming work through the data the machine provides. This might seem very impersonal, but as resulted from the interviews, employees see this information as a positive asset to overview their workflow and performances. It enhances the empathy to the company as employees have an insight on how their performance influences the production and motivates them to be even more productive.

Research question 3: *What are the key features needed enabling real time insights to best serve industry professionals?*

In the initial design iterations only the most central key performance indicator was presented to the target audience. The 24-hour trailing spindle up time. This was the actual time that the spindle of the production machine was moving in a CNC program, divided by a 24-hour trailing clock. In the interviews of Chapter 4 this was evaluated to be insufficient to enable real time insights. Too much of the context surrounding this KPI was lost in simplification of the design. An iteration of the interface design brought with it an iteration in KPI design. The KPI was reintroduced with the Overall Equipment Effectiveness standard of development. This resulted in a real time display of the Net run time OEE. Scheduled, availability and performance losses are incorporated into this KPI, leaving only the quality loss to be reported after the fact.

For manufacturing operations that require more context with the OEE, or have not effectively implemented the OEE standard, another display interface is developed. The 24-hour trailing display provides the parameters of quantity of produced parts, number of different parts, average batch size, average cycle time, average changeover time and the machine power on time. These parameters help provide context in manufacturing operations with a large portfolio of products requiring flexibility in their production.

Research question 4: *How do the proposed design and implementation framework improve the production process?*

The proposed design helps improve the production process by providing real time insights into the manufacturing operation. Gaining access to objective, transparent metrics relevant to production helps identify problems, evaluate performance and identify areas for improvement. The addition of a forward-looking feature, as described in Chapter 5, presenting the necessary raw material, program and tools needed leads to reduced setup times and errors in the production process. These metrics can then be evaluated, improvements validated through the production KPIs.

Main Question: *How can manufacturing SMEs with legacy production assets enable real time insights into their component-based production process?*

A low-cost solution provides similar or greater capabilities compared to solutions tailored towards enterprise, available commercially. This gives manufacturing SMEs insights into their respective manufacturing operation with little financial or knowledge requirements. Large manufacturing operations could follow this example, but scale advantages dilute the cost difference between the two implementation concepts. Relying on after-sales service for system performance guarantees tends to point enterprise adoptors in the commercial direction.

Implementing a lightweight interface design with limited infrastructure investment connected to legacy production assets can enable real time insights into the manufacturing process. Following the best practices and design guidelines presented in Chapter 5 aids the implementing engineering team in making prudent choices in presenting information to the right stakeholder. Having universal access to transparent production metrics can help them improve their production process and help achieve efficiency gains. Operators can plan ahead with access to planning, upcoming programs and tools. Middle management gains resource planning abilities and performance evaluation data of individual machines. Live monitoring of machine status can quickly provide intervention stimulus to solve issues faster. Top level management gains big-picture live data and can identify problems in real time. Automated reporting of manufacturing data in weekly, monthly and quarterly fashion helps track the manufacturing process over time. This provides a contribution to the knowledge gap of giving manufacturing SMEs an implementation method on how to incorporate real time insights into their manufacturing operation.

There have been several limitations to the research carried out in this thesis report. The focus of this thesis research has been on the component-based production processes common in small and medium-sized enterprises. This aspect limits the generalizability to other SME manufacturers, which are active in different manufacturing processes. The limited amount of different manufacturing companies and subjects interviewed can be seen as a limitation, as the point of view of organizations can differ greatly with regards to the thesis research. Extending the amount of companies and interviewees presented with a live prototype can provide more useful feedback resulting in a better end product. These limitations, developing possible solutions and creating a fully functional prototype are left for future research.

This thesis research has relevance in a multitude of ways. At the foremost this thesis is relevant in the practical business sense, that it helps small and medium sized enterprises gain real time insights into their manufacturing process, resulting in production efficiency gains and identify process improvements. These factors help manufacturing SMEs stay close to their ambitions in an ever-increasingly competitive global business climate.

In a scientific context, this thesis is relevant as it used the latest scientific knowledge to analyse a complex problem and methodically design a comprehensive, relevant solution. Utilizing design methodology from different fields of science to construct a fitting lightweight design solution to a previously abstract problem helped raise awareness for the issue in the target audience, creating incentive for commercial parties to come up with in-house developed solutions.

The thesis research and the prototype designs are relevant to the field of Management of Technology in the sense that it connects technical engineering challenges to the managerial and administrative solutions of a modern connected manufacturing operation. The way this thesis is set up, is to overcome these challenges by involving relevant parties and creating a fitting for them. The outcome of these challenges are beneficial in aiding the making of business decisions based on objective data and technical knowledge. These factors make the case that this is exactly what a Management of Technology related multi-disciplinary research project should be comprised of.

Bibliography

[1] Omolola A. Adeoye-Olatunde and Nicole L. Olenik. "Research and scholarly methods: Semi-structured interviews". In: *Journal of the American College of Clinical Pharmacy* 4 (10 Oct. 2021), pp. 1358–1367. ISSN: 2574-9870. DOI: 10.1002/JAC5.1441. URL: https://onlinelibrary.wiley.com/doi/full/10.1002/jac5.1441%20https://onlinelibrary.wiley.com/doi/abs/10.1002/jac5.1441%20https://accpjournals.onlinelibrary.wiley.com/doi/10.1002/jac5.1441.

[2] Onur Agca et al. "An Industry 4 readiness assessment tool". In: (2016). URL: www.warwick.ac.uk/scip1.

[3] Abdulrahman Alqoud, Dirk Schaefer, and Jelena Milisavljevic-Syed. "Industry 4.0: a systematic review of legacy manufacturing system digital retrofitting". In: *Manufacturing Review* 9 (2022), p. 32. ISSN: 2265-4224. DOI: 10.1051/MFREVIEW/2022031. URL: https://mfr.edp-open.org/articles/mfreview/full_html/2022/01/mfreview220051/mfreview220051.html%20https://mfr.edp-open.org/articles/mfreview/abs/2022/01/mfreview220051/mfreview220051.html.

[4] Amir Azizi. "Evaluation Improvement of Production Productivity Performance using Statistical Process Control, Overall Equipment Efficiency, and Autonomous Maintenance". In: *Procedia Manufacturing* 2 (Jan. 2015), pp. 186–190. ISSN: 2351-9789. DOI: 10.1016/J.PROMFG.2015.07.032.

[5] Shelly Bagchi and Jeremy A Marvel. "Towards Augmented Reality Interfaces for Human-Robot Interaction in Manufacturing Environments". In: (2018). DOI: 10.1145/nnnnnnn.nnnnnnn. URL: https://doi.org/10.1145/nnnnnnn.nnnnnnn.

[6] Kimberly A. Bates and E. James Flynn. "INNOVATION HISTORY AND COMPETITIVE ADVANTAGE: A RESOURCE-BASED VIEW ANALYSIS OF MANUFACTURING TECHNOLOGY INNOVATIONS." In: *https://doi.org/10.5465/ambpp.1995.17536502* 1995 (1 Dec. 2017), pp. 235–239. ISSN: 0065-0668. DOI: 10.5465/AMBPP.1995.17536502. URL: https://journals.aom.org/doi/abs/10.5465/ambpp.1995.17536502.

[7] Hugh Boyes et al. "The industrial internet of things (IIoT): An analysis framework". In: *Computers in Industry* 101 (Oct. 2018), pp. 1–12. ISSN: 0166-3615. DOI: 10.1016/J.COMPIND.2018.04.015.

[8] Bernadette Dierckx de Casterle et al. "QUAGOL: a guide for qualitative data analysis". In: *International journal of nursing studies* 49 (3 Mar. 2012), pp. 360–371. ISSN: 1873-491X. DOI: 10.1016/J.IJNURSTU.2011.09.012. URL: https://pubmed.ncbi.nlm.nih.gov/21996649/.

[9] Alan Cooper, Robert Reimann, and Dave Cronin. "About Face 3: The Essentials of Interaction Design, Third Edition". In: (2004).

[10] Alan Cooper, Robert Reimann, and Dave Cronin. "About Face 3: The Essentials of Interaction Design, Third Edition". In: (2007).

[11] Alan Dix. "Human–computer interaction, foundations and new paradigms". In: *Journal of Visual Languages Computing* 42 (Oct. 2017), pp. 122–134. ISSN: 1045-926X. DOI: 10.1016/J.JVLC.2016.04.001.

[12] Miren Estensoro et al. "A resource-based view on SMEs regarding the transition to more sophisticated stages of industry 4.0". In: *European Management Journal* (Oct. 2021). ISSN: 0263-2373. DOI: 10.1016/J.EMJ.2021.10.001.

[13] Matthew Fulton and Bernard Hon. "Managing advanced manufacturing technology (AMT) implementation in manufacturing SMEs". In: *International Journal of Productivity and Performance Management* 59 (4 2010), pp. 351–371. ISSN: 17410401. DOI: 10.1108/17410401011038900/FULL/PDF.

[14] Alan Hevner et al. "Design Science in Information Systems Research". In: *Management Information Systems Quarterly* 28 (Mar. 2004), pp. 75–.

[15] Muhammad Imran et al. “Resource and Information Access for SME Sustainability in the Era of IR 4.0: The Mediating and Moderating Roles of Innovation Capability and Management Commitment”. In: *Processes* 7.4 (2019). ISSN: 2227-9717. DOI: 10.3390/pr7040211. URL: https://www.mdpi.com/2227-9717/7/4/211.

[16] *ISO 9241-210:2019 - Ergonomics of human-system interaction — Part 210: Human-centred design for interactive systems*. URL: https://www.iso.org/standard/77520.html.

[17] Pritchard J. “Robotics company FANUC on why it is well placed to help the eVTOL aircraft and UAM markets - eVTOL Insights”. In: *eVTOL Insights* (2022). URL: https://evtolinsights.com/2022/08/robotics-company-fanuc-on-why-it-is-well-placed-to-help-the-evtol-aircraft-and-uam-markets/.

[18] Ying J. “What is Haas Control Fanuc Control - Difference Between Haas and Fanuc”. In: *CNCLathing* (Nov. 2020). URL: https://www.cnclathing.com/guide/what-is-haas-control-fanuc-control-difference-between-haas-and-fanuc-cnclathing.

[19] Hanna Kallio et al. “Systematic methodological review: developing a framework for a qualitative semi-structured interview guide”. In: *Journal of Advanced Nursing* 72 (12 Dec. 2016), pp. 2954–2965. ISSN: 1365-2648. DOI: 10.1111/JAN.13031. URL: https://onlinelibrary.wiley.com/doi/full/10.1111/jan.13031%20https://onlinelibrary.wiley.com/doi/abs/10.1111/jan.13031%20https://onlinelibrary.wiley.com/doi/10.1111/jan.13031.

[20] P. Kopacek. “Development Trends in Cost Oriented Production Automation”. In: *IFAC-PapersOnLine* 51 (30 Jan. 2018), pp. 39–43. ISSN: 2405-8963. DOI: 10.1016/J.IFACOL.2018.11.242.

[21] Noah K Lee. “Total Automation: The Possibility of Lights-Out Manufacturing in Total Automation: The Possibility of Lights-Out Manufacturing in the Near Future the Near Future”. In: (2018). URL: https://scholarsmine.mst.edu/peer2peer/vol2/iss1/4.

[22] Jeffrey K Liker. “The Toyota Way: 14 Management Principles from the World’s Greatest Manufacturer”. In: (2004).

[23] Shane Loughlin. “Industry 3.0 to Industry 4.0: Exploring the Transition”. In: *New Trends in Industrial Automation* (Nov. 2018). DOI: 10.5772/INTECHOPEN.80347. URL: undefined/state.item.id.

[24] Tariq Masood and Paul Sonntag. “Industry 4.0: Adoption challenges and benefits for SMEs”. In: *Computers in Industry* 121 (Oct. 2020), p. 103261. ISSN: 0166-3615. DOI: 10.1016/J.COMPIND.2020.103261.

[25] Jeroen De Mast and Joran Lokkerbol. “An analysis of the Six Sigma DMAIC method from the perspective of problem solving”. In: *International Journal of Production Economics* 139 (2 Oct. 2012), pp. 604–614. ISSN: 0925-5273. DOI: 10.1016/J.IJPE.2012.05.035.

[26] Dominik T. Matt, Vladimír Modrák, and Helmut Zsifkovits. “Industry 4.0 for smes: Challenges, opportunities and requirements”. In: *Industry 4.0 for SMEs: Challenges, Opportunities and Requirements* (Jan. 2020), pp. 1–401. DOI: 10.1007/978-3-030-25425-4/COVER.

[27] Alexander Osterwalder et al. “The Invincible Company Business Model Strategies From the World’s Best Products, Services, and Organizations”. In: (2020).

[28] Jan C. van Ours and Lenny Stoeldraijer. “Age, wage and productivity in Dutch manufacturing”. In: *Economist* 159 (2 June 2011), pp. 113–137. ISSN: 0013063X. DOI: 10.1007/S10645-011-9159-4/METRICS. URL: https://link.springer.com/article/10.1007/s10645-011-9159-4.

[29] Matthew J. Page et al. “The PRISMA 2020 statement: An updated guideline for reporting systematic reviews”. In: *PLOS Medicine* 18 (3 Mar. 2021), e1003583. ISSN: 1549-1676. DOI: 10.1371/JOURNAL.PMED.1003583. URL: https://journals.plos.org/plosmedicine/article?id=10.1371/journal.pmed.1003583.

[30] Ken Peffers et al. “A design science research methodology for information systems research”. In: *Journal of Management Information Systems* 24 (3 Dec. 2007), pp. 45–77. ISSN: 07421222. DOI: 10.2753/MIS0742-1222240302. URL: https://www.tandfonline.com/action/journalInformation?journalCode=mmis20.

[31] Thomas Pyzdek et al. *Six Sigma Handbook: A Complete Guide for Green Belts, Black Belts, and Managers at All Levels, Third Edition*. McGraw-Hill Education, 2010, pp. 3–209. ISBN: 9780071623384. URL: https://www.accessengineeringlibrary.com/content/book/9780071623384%20https://www.accessengineeringlibrary.com/content/book/9780071623384.abstract.

[32] Karen Rose, Scott Eldridge, and Lyman Chapin. "The Internet of Things: An Overview Understanding the Issues and Challenges of a More Connected World". In: (2015).

[33] Christoph Roser. "Faster, Better, Cheaper in the History of Manufacturing : From the Stone Age to Lean Manufacturing and Beyond". In: *Faster, Better, Cheaper in the History of Manufacturing* (Oct. 2016). DOI: 10.1201/9781315367941. URL: https://www.taylorfrancis.com/books/mono/10.1201/9781315367941/faster-better-cheaper-history-manufacturing-christoph-roser.

[34] Devansh Sanghavi, Sahil Parikh, and S. Aravind Raj. "Industry 4.0: Tools and implementation". In: *Management and Production Engineering Review* 10 (3 2019), pp. 3–13. ISSN: 20821344. DOI: 10.24425/MPER.2019.129593. URL: https://www.researchgate.net/publication/336125411_INDUSTRY_40_TOOLS_AND_IMPLEMENTATION.

[35] "Six Sigma: a goal-theoretic perspective". In: *Journal of Operations Management* 21 (2003), pp. 193–203.

[36] Michael Sony and Subhash Naik. "Key ingredients for evaluating Industry 4.0 readiness for organizations: a literature review". In: *Benchmarking* 27 (7 Aug. 2020), pp. 2213–2232. ISSN: 14635771. DOI: 10.1108/BIJ-09-2018-0284.

[37] Tim Stobierski. "The Advantages of Data-Driven Decision-Making". In: (2019). URL: https://online.hbs.edu/blog/post/data-driven-decision-making.

[38] R. Sundar, A. N. Balaji, and R. M. Satheesh Kumar. "A Review on Lean Manufacturing Implementation Techniques". In: *Procedia Engineering* 97 (Jan. 2014), pp. 1875–1885. ISSN: 1877-7058. DOI: 10.1016/J.PROENG.2014.12.341.

[39] Allan Sylvester, Mary Tate, and David Johnstone. "Beyond synthesis: re-presenting heterogeneous research literature". In: *http://dx.doi.org/10.1080/0144929X.2011.624633* 32 (12 Dec. 2011), pp. 1199–1215. ISSN: 0144929X. DOI: 10.1080/0144929X.2011.624633. URL: https://www.tandfonline.com/doi/abs/10.1080/0144929X.2011.624633.

[40] Khalid Hasan Tantawi, Alexandr Sokolov, and Omar Tantawi. *Advances in industrial robotics: From industry 3.0 automation to industry 4.0 collaboration*. IEEE. 2019.

[41] A. J. Thomas, R. Barton, and E. G. John. "Advanced manufacturing technology implementation: A review of benefits and a model for change". In: *International Journal of Productivity and Performance Management* 57 (2 2008), pp. 156–176. ISSN: 17410401. DOI: 10.1108/17410400810847410/FULL/PDF.

[42] Nicholas S. Vonortas and Lan Xue. "Process innovation in small firms: Case studies on CNC machine tools". In: *Technovation* 17 (8 Aug. 1997), pp. 427–438. ISSN: 0166-4972. DOI: 10.1016/S0166-4972(97)00016-3.

[43] MacDougal W. "Industrie 4.0 - Smart Manufacturing for the Future". In: *Trade Invest* (2014). URL: https://www.gtai.de/en/invest/service/publications/industrie-4-0-germany-market-report-and-outlook-64602.

[44] Bonvillian William and Singer Peter. *Advanced Manufacturing*. 2018. URL: https://mitpress.mit.edu/9780262037037/advanced-manufacturing/.

[45] J. P. Womack and D. T. Jones. "Lean thinking−banish waste and create wealth in your corporation". In: *Journal of the Operational Research Society* 48 (11 Dec. 1997), p. 1148. ISSN: 14769360. DOI: 10.1057/PALGRAVE.JORS.2600967/METRICS. URL: https://link-springer-com.tudelft.idm.oclc.org/article/10.1057/palgrave.jors.2600967.

[46] New York et al. *Six Sigma Way: How to Maximize the Impact of Your Change and Improvement Efforts*. McGraw-Hill Education, 2014. ISBN: 9780071497329. URL: https://www.accessengineeringlibrary.com/content/book/9780071497329%20https://www.accessengineeringlibrary.com/content/book/9780071497329.abstract.

A

Appendix A - Planning

A.1. Planning

On the next page, a planning overview is displayed. Major activities are divided into specific research activities and are linked to a time frame. A midterm meeting is planned in week 11, but the thesis committee and researcher will have to discuss what is expected or necessary with regards to this activity.

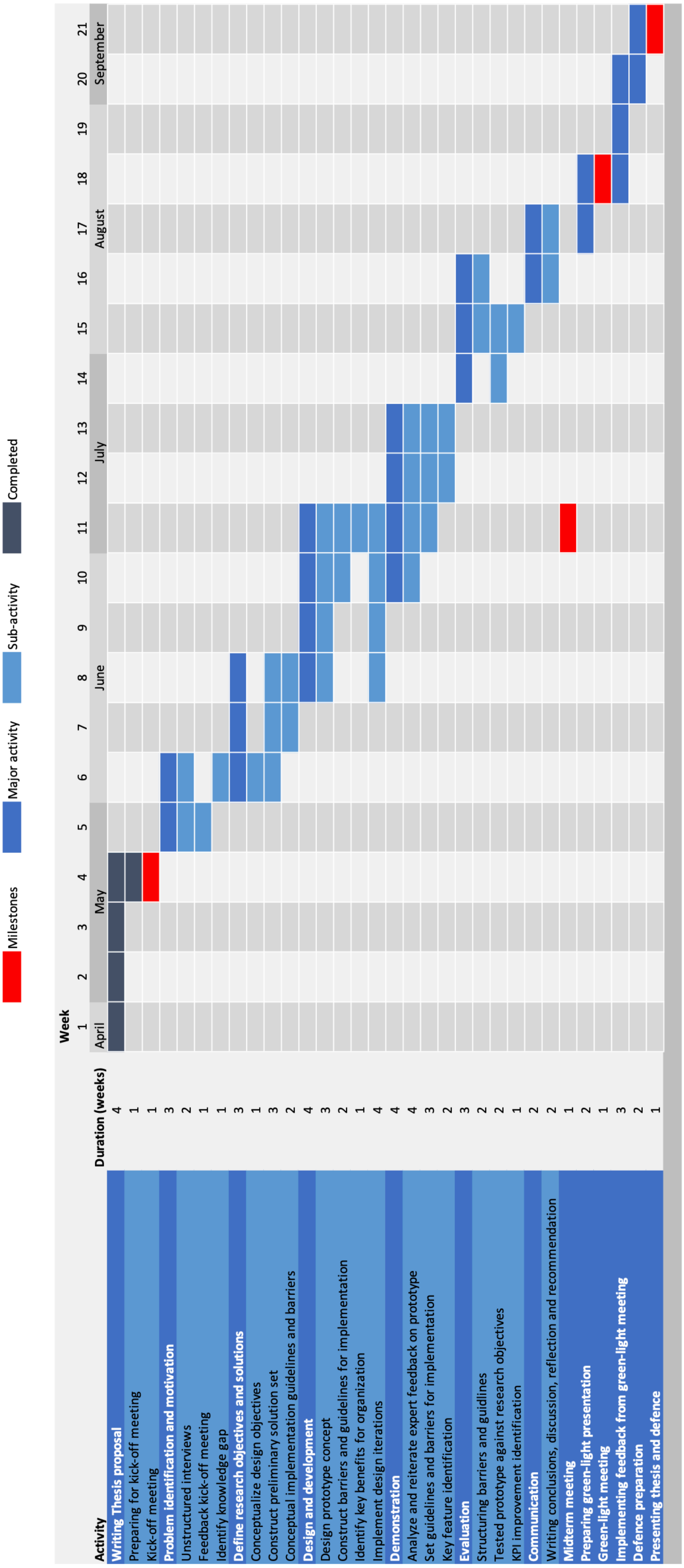

Figure A.1: Master thesis planning Gantt chart

B

Appendix B - Interviews

This Appendix goes into the interview aspect of the thesis research with all relevant components of this research aspect and their respective evolution.

B.1. Methodology

In this section, the methodology for the interview procedure and analysis is visualised. Please refer back to Chapter 4 for a more comprehensive overview.

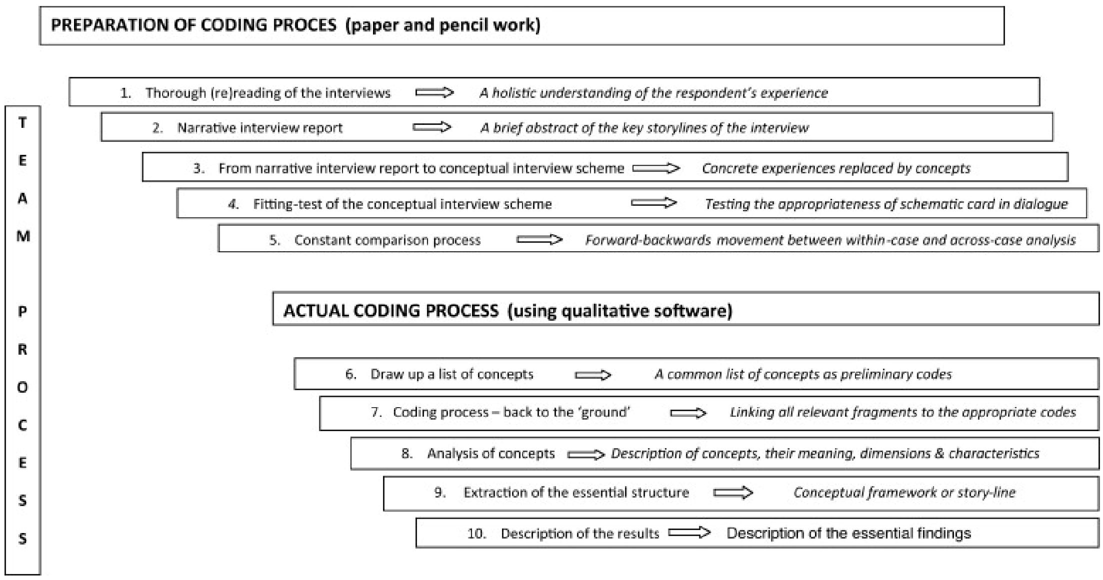

Figure B.1: Qualitative Analysis Guide of Leuven Methodology process model

B.2. Interviewees

For the research to have a significant value, a grounded selection of interviewees should be done. Within a specific organization, interviewees from different levels in the companies are selected. Important is that the interviewees often have interactions with each other, so the values from different stakeholders can be identified with relation to the problem at hand.

ID	Category	Domain	Role and job activities
D1	Director	Technical, engineering, sales	Director in a mid-sized technology company, overseeing technical development and sales engineering.
D2	Director	General management, technical	C-level director on company group level. Determining strategic goals and management KPIs.
D3	Director	Management, production engineering	General director in medium sized production enterprise. Leading a team of approximately 130 people. Setting goals and KPIs on department level.
D4	Director	Management, engineering, sales	C-level director on company group level. Determining strategic goals and management KPIs.
M1	Manager	Engineering, production	Shopfloor manager on the production floor of a medium-sized company. Leading a team of around 15 operators.
M2	Manager	Production, management	Shopfloor manager on the production floor of a medium-sized company. Is in charge of a team of around 65 operators.
M3	Manager	Quality, production engineering	Manager in the quality department of a medium-sized company. Is in charge of a team of three quality personnel. Ensures in-line quality control and the end of production quality control.
M4	Manager	Quality, production engineering	Manager in the quality department of a medium-sized company. Is in charge of a team of three quality personnel. Ensures in-line quality control and the end of production quality control.
M5	Manager	Production, operations	Manager in the production department of a medium-sized company. Leads a production team of about 10 production personnel. Is in charge of initiating production orders, ensuring progression and ultimately responsible for on-time delivery.
E1	Engineer	Engineering, automation, production	Automation engineer in a medium-sized enterprise. Implementing automation solutions into existing production processes. Updating machines to modern standards.
E2	Engineer	Engineering, automation, design	Design engineer in a small team, working design solutions for automation purposes. Producing prototypes for automation designs.
E3	Engineer	Work preparation, production	Mechanical engineer in charge of work preparation at a medium-sized company. Leading production planning, material flow, stock levels and ensuring productivity levels on the shopfloor.

E4	Engineer	Production, work preparation	Mechanical engineer, in charge of programming CNC equipment. Provides programs to the operator, optimizes production process. Selects tools and production strategies.
E5	Engineer	Design, development	Mechanical engineer, in charge of product development en product design on machine level. Producing a mechanical design, making iterative design improvements, communicating with production.
O1	Operator	Production, engineering	CNC operator of large milling machines in a medium-sized enterprise. Working one or more machines at the same time.
O2	Operator	Production	Operator in work preparation for the CNC production department in a medium-sized enterprise. Operates the automatic saw and prepares raw material for further processing.
O3	Operator	Production, engineering	Operator in the CNC department of a medium-sized company. In charge of running the machines and ensuring efficiency. Does programming of the machines and makes production reports.

Table B.1: Overview of interviewees and their respective roles.

B.3. Summaries

In this section, the interview summaries for each interview are given. This has an effect on the design stage and the final design.

ID	Interview summary
D1	The interviewee, with a background in mechanical and aerospace engineering, emphasized the critical need to enhance parts production planning. He highlighted the importance of real-time monitoring of production assets, suggesting that tracking the status of individual parts leads to improved client communication and accurate lead times. This monitoring can identify bottlenecks, enabling efficient production planning and capacity shifting among production systems. He underscored the significance of having clear processes for ordering, invoicing, and insights into parts' status. Real-time data benefits operators and managers, while trend analysis aids top-level management decisions. Accurate, timely information is crucial for updating customers and tracking specific parts in the production chain. The interviewee recommended methods like big display systems for immediate insights and advised starting with incremental improvements and rapid data automation. They stressed the value of understanding milling variations and envision a system that offers insights into the time taken for parts production, emphasizing efficient workload balance in the engineering department.
D2	The individual, with a background in ship engineering and a directorial role at Tetra-Pak, emphasized the pivotal role of production standardization and process control in enhancing productivity. Having acquired AV Flexologic, they led the development of products for the packaging industry, establishing market leadership. The significance of production monitoring was highlighted as a tool for boosting output and reducing defects. Implementing these systems demands the collaboration of stakeholders, including management, operators, and floor managers. The importance of visuals, real-time insights, and tools in streamlining processes was underlined. While the challenges of implementing change and breaking conventions are evident, the focus remains on continuous improvement and keeping the operator contented. Emphasis was placed on context-rich KPIs, departmental information, and operator efficiency. Concepts like 'just in time' parts delivery, limiting stock to three months' worth, and avoiding large batch processing for efficiency were stressed. The core message was balancing capacity, optimizing planning, and continually refining the production process for quality.
D3	The interviewee emphasized the significance of merging technology, knowledge, and human input to enhance production efficiency. They believe that achieving real-time insights is paramount to this endeavor. While the introduction of new equipment can present initial challenges, the critical aspect lies in understanding the current status of parts. They advocate for weekly monitoring, preferably through email reports, and underscore the primacy of financial performance. Delving into the industry's nuances, the interviewee highlighted the potential of technologies like ERP systems for tracking production. Discipline, knowledge, and hands-on experience are pivotal in refining monitoring mechanisms. The interviewee suggests that present data representation designs may need fine-tuning to cater to varied stakeholder needs, emphasizing the importance of context in identifying improvement areas. Striking a balance between comprehensive data and avoiding an information overload is essential. The interviewee prefers outcome-centric insights over granular details and stresses the importance of preparedness in discussions. They question excessive display systems, emphasizing concise, focused content. Open to feedback, the participant welcomes further discussions and prototype refinements.

D4	The interviewee, a managing director with a background in mechanical engineering, stresses the significance of implementing real-time production monitoring to enhance efficiency. While the current systems are mainly administrative, there's a gap in operational monitoring. To truly elevate production efficiency, planning should be seamlessly integrated into the system, and context is essential for comprehensive machine performance evaluation. The interviewee reveals a prototype system tailored for various stakeholders, such as operators and managers. This system offers real-time updates, KPIs, and alerts, alongside departmental monitoring and reporting features. As they delve into the challenges of benchmarking machine performance, factors like uptime, idle time, and part production come to the fore. The interviewee suggests referencing literature for display guidance and emphasizes the importance of connecting analysis to their new ERP system. Favoring continuous improvement, the approach should begin with a minimum viable product, ensuring iterative enhancement without overwhelming the system with features.
M1	The interview centers on real-time insights and the implementation of industry 4.0 technologies in small and medium-sized manufacturing enterprises. Presently, machine monitoring is done manually with data printed and showcased on boards. The researcher introduces a design concept for a system that not only displays machine data but also offers performance metrics for various personnel levels. The interviewee highlights the potential benefits of viewing upcoming program details, suggesting that this feature could lead to significant efficiency improvements. Furthermore, insights into tool preparation, shift performance comparisons, and an operator performance overview are discussed. The interviewee also mentions the difficulty of comparing KPIs without adequate context, emphasizing the need for comprehensive data and weekly or monthly email reports. Throughout, the overarching goal is to comprehend the full scope of advantages and requirements of real-time insights within manufacturing processes. The conversation concludes with the user's gratitude for the interview opportunity.
M2	The interview focused on the transition to real-time insights within the component-based production process. Currently, systems are not real-time and need human intervention, with existing ERP systems falling short for real-time monitoring. The expert stressed that such insights offer a detailed view into worker activities, project status, and efficiencies. Key benefits include real-time data on material use, labor, efficiency, and costs. Implementing such a system, however, comes with challenges like finding an apt ERP solution and addressing management's hesitance towards change. While individual performance metrics are desired, aggregate efficiency per department is seen as vital, coupled with simple reporting methods for evaluations. The interview also delved into data visualization, showcasing a prototype display for various production stakeholders. The expert underscored that upper management holds the key to facilitating the change and emphasized the necessity of standardized reporting. The conversation wrapped up without additional points.
M3	The interviewee, the quality manager of the Caller Control Support Group, has worked with the company for nine years, initially as a 3D printer tester before transitioning to the app side and producing machines with flexible industry logic. He believes real-time data visualization of the production floor is crucial for enhancing efficiency. While he acknowledges that quality can be ascertained only after production, he emphasizes the significance of clear procedures and robust feedback mechanisms. Effective planning and the display of part-making instructions are vital. He sees immense value in inter-departmental communication, especially concerning part quality. The prototype visualization screen designed for the CNC department is seen as beneficial for planning and production time estimation. Though he doesn't deem a separate screen for the quality department necessary, he suggests its potential utility for the work preparation department. The interview concluded with the manager feeling the main points were addressed adequately.

M4	The interviewee, who progressed from a mechanic to a quality manager, discusses the current challenges in monitoring. Presently, data is manually entered and not in real-time, with much of the information being relayed through emails. Emphasizing the significance of real-time insights, he believes it can enhance planning for asset downtime and help in formulating a realistic production schedule. He advocates for performance comparisons between operators to optimize output and efficiency and suggests weekly reporting via email or Excel. Drawing from his experience using a cloud-based management tool to track issues and boost inter-departmental communication, he proposes a similar cloud-based system to track each machine's entire history. However, he acknowledges the obstacles of ineffective communication and the absence of a cohesive ERP system, asserting that managerial intervention is essential to surpass these challenges and implement desired changes.
M5	The interviewee, with a rich background in production and purchasing, has witnessed the company's evolution through various stages of production, including shifts between insourcing and outsourcing in Holland and Romania. He values the advantages of inhouse control for enhanced coordination and management. Currently, weekly production meetings adjust the production planning based on capacity, and real-time insights are favored for the on-site production team in Romania. In contrast, higher-level reports are more suited for management. Learning from past mistakes, he underlines the need for strengthened communication between engineering and the production floor to circumvent misunderstandings. To boost efficiency, he advocates for standardization, effective inter-departmental communication, and tools that ensure clear information transfer, including data visualization. Recommendations include detailed lists of required materials and tools, tracking material progress, and regular communication mechanisms like monthly planning sessions or message boards. Ultimately, streamlined communication could refine production processes and minimize waste.
E1	The automation engineer emphasizes the significance of real-time monitoring in the production process, highlighting its potential in identifying machine downtime and enhancing productivity. Essential data points include cycle times, machine on/off times, and tool life cycle times. Benefits derived from such real-time insights range from downtime elimination and production boost to optimized maintenance and extended machine life cycles. Sabo envisions a three-screen prototype for different organizational levels, showcasing vital data like current production status, parts produced, and uptime. He proposes color-coded indicators for instant performance assessment and integration of target planning. Furthermore, they see potential in operators logging into machines to track their performance. In essence, while operators focus on their tasks, shift managers should analyze the derived data. Additional screens could benefit the service team, displaying technical data and monitoring machine health. Incorporating break times and clear machine status indicators would also enhance monitoring efficiency.
E2	The mechanical engineer interviewee sees significant potential in implementing real-time monitoring of production assets for the company. While such a system is not currently in place, its benefits include a clear daily production overview, aiding in goal-setting, resource allocation, and fostering competition among operators. He finds the presented design concepts appealing, especially the attention to individual machines. He suggests additional features: tracking parts' progress and displaying machine downtime reasons. Operators having a clear view of their performance, being able to compare with peers, and inputting data would be beneficial. The overarching emphasis is on the system's ability to improve resource distribution, process enhancement, and planning. He also believes that proactive maintenance alerts and communication about planned downtimes are essential for smooth operations. In essence, real-time monitoring is vital for both management decision-making and operator performance insights, coupled with the need for efficient maintenance communication.

E3	The work operation manager from Korean Control Support highlights that their current monitoring systems are outdated and merely offer after-the-fact, high-level views without detailed status. Manual data entry, prone to errors and laziness, is not seen as an ideal approach. Drawing from his experience in managing technical means and databases, he emphasizes the significant advantages of real-time insights, believing they can boost production output and quality, benefiting all company stakeholders. The manager has implemented an ERP system and stock managing system, further stressing the importance of modular systems. Such systems permit customization and provide flexibility to integrate new features, ensuring tailored statistics and analysis as required. In essence, the manager champions the transition to real-time, customizable, and modular monitoring systems for optimal production and stakeholder benefits.
E4	the interviewee, process engineer in production, stresses the importance of program optimization and ensuring tools are effectively utilized for machine operations. Current monitoring is done on a weekly basis, highlighting the significance of accurate efficiency data per machine. He underscores that while legacy machines can still provide value, maintenance scheduling is pivotal for performance. Real-time insights into machine operations are essential, including metrics like runtime, stoppage, and setup times. An efficient system should encompass the flow of materials, program information, and tools. Emergency scheduling and custom changeover times for specific part-machine combinations are also crucial. While operators need simplified, task-relevant data, other team members might need detailed information. He believes in understanding the interplay between machines, operators, and tools for effective programming. He emphasizes the importance of proactive planning and the potential need for more staff in material cutting to boost efficiency. The discussed concepts were well-received, with all major aspects addressed.
E5	The senior engineer at a machine manufacturing company has no prior experience with monitoring systems but sees significant potential in real-time production monitoring. He believes it can enhance tracking of production time, streamline work processes, and ensure consistent quality. Key features he suggests include feedback mechanisms to the design from production, real-time status updates of individual parts, operation durations, and setup lists. Furthermore, the capacity to switch between different production systems could boost output. Information about machine status, production data, tool life, parts count, batch size, and key performance indicators would be invaluable for various stakeholders. The engineer also underlines the importance of fostering communication between production and purchasing departments, asserting that real-time monitoring can instantly address issues, foster competitiveness among operations, and strengthen overall company cohesion.
O1	An investigation into enabling real-time insights from legacy production assets in manufacturing SMEs involved interviews with industry professionals. One interviewee, with a background as an operator, shared that his former employers monitored machine performance using stopwatches. He highlighted the value of real-time insights, emphasizing the potential to optimize production by understanding machine runtime. This would allow operators to multitask, working on other machines during downtimes. He suggests that machine status, especially the remaining runtime, should be made easily visible to enable efficient task management, proposing features like simple timers. While he's not keen on alarms, he believes in the merit of a visual planning system over verbal communication. The design division catering to specific roles was also well-received by the interviewee. He feels that comprehensive data, potentially in Excel format, should be easily accessible, covering aspects from design modifications to maintenance and tools.

O2	The interviewee emphasizes the value of real-time monitoring in enhancing machine performance and process improvement, potentially leading to a 30% increase in performance. Currently relying on verbal communication and WhatsApp for updates, he sees a crucial need for efficient planning, particularly regarding upcoming parts, their quantities, and their subsequent locations, which aids in job planning for the sawing machine. The idea of displays showing machine data and performance metrics appeals to him, favoring the transparency it offers across different organizational levels. Efficient data collection, possibly by an engineer or operator, and having necessary parts closer to workstations can further drive productivity. He suggests the display should clearly illustrate the relationship between parts and performance, including time lost during machine changeovers. Reducing time wasted due to incorrect material retrieval is also a priority. Overall, the interviewee is content with the discussion and the presented concepts.
O3	The interviewee receives production information primarily through physical methods like paper and verbally, with some reliance on emails and managers. This existing system leads to inefficiencies, especially when rush jobs disrupt regularly planned tasks. While the actual machine runtime is seen as crucial, there's a recognized need to improve communication between production and design. For efficiency, it's essential to have information readily available for the next job. He acknowledges the role of financial KPIs for top-level management. Although the programmer might not need a dedicated screen, planning screens could be beneficial for optimization. However, there's a cautionary note on idle time data to prevent pressuring operators into mistakes. Robots could potentially aid in machine setup, but require optimization and operator engagement. The speaker highlights challenges like receiving poor-quality drawings and the costs of specialized tools, suggesting that enhanced inter-departmental communication could lead to improved production outcomes.

Table B.2: Overview of interview summaries.

ID	Name	Description	Code group
C1	Absence of target setting	Interviewee indicates that there is a lack of target setting and evaluating.	Communication barriers
C2	Confusion	Interviewee indicates that there exists a general confusion in the priorities of production.	Communication barriers
C3	Frustration	Interviewee indicates that there is frustration among the production employees coming from mixed communication.	Communication barriers
C4	Inefficiency	Interviewee indicates that there is an innefficient way of communication at the present time.	Communication barriers
C5	Uncertainty	Interviewee indicates that there are times of uncertainty in the communication and what needs to happen.	Communication barriers
C6	Lack of clarity	Interviewee indicates that there is a lack of clarity what needs to happen in the production or what is actually happening.	Communication barriers
C7	Capacity planning	Interviewee indicates that to increase efficiency, an accurate capacity planning is needed.	Business operations
C8	Logistics	Interviewee indicates that to increase efficiency, the logistics of the manufacturing operations need to be on point.	Business operations

C9	Manufacturing	Interviewee indicates that to increase efficiency, a real time status of the manufacturing operation is needed.	Business operations
C10	Process improvement	Interviewee indicates that to gain real time insights, iterative process improvement is preferable.	Business operations

Table B.3: Code ID, names, descriptions and respective code groups.

B.4. Evolution of interview guide

In this section, the complete evolution of the interview guide is given. In short, the first evolutions of questions would have been extremely long to complete the interviews. The interview guide has been adapted to become more focused and to the point for more effective questioning. In Chapter 4 a more in-depth guide on the interviews is given and the reason behind the questioning and its evolution.

B.4.1. Introduction

- What industry would you most associate your company with?
- What is your position within the company?
- What are your main responsibilities within the organization?
- What is your experience with real time monitoring of production assets? Production machines -
- What is your experience with real time monitoring of business processes?
- How do you use the data gathered/generated/displayed by these processes?
- What do you think of the effect real time insights have on an organization?
- What do you think of the effect real time insights have on the individual employee?

B.4.2. Requirements and guidelines

- Could you describe the process of gaining insights in the production process in your company?
- How did you implement this process?
- Who are the stakeholders involved?
- Looking back, how would you rate the implementation of this process?
- What barriers were most prevalent in the implementation of this system?
- Are there areas of the production process that were hard to gain insights in?
- Are there areas of the production process that were easy to gain insights in?
- What would you see as the next step or part of the production process to gain insights into?
- What would need to be resolved or implemented before this could become a reality?

B.4.3. Benefit identification

- What is, in your opinion, the most crucial benefit of gaining real time insights into your production process?
- What is the effect of this benefit?
- Who are the stakeholders that benefit from this?
- How is this benefit used by the stakeholders?
- How does this influence the production process?
- How does this influence the organization?

B.4.4. Key features

- What are the most useful features that are built into the real time insights solution?
- How do you use these features?
- What effect do they have on your workflow?
- What features would you like to see in a future iteration?
- How would this impact your workflow?
- What features would you rate superfluous to the real time insights?
- Could you please state the reason for this?

B.4.5. Concluding

- What was the most impactful change needed in the company to implement real time insights?
- What were the key players involved in implementing the real time insights solution?
- What outside help did you need for the implementation of the solution?
- How did you evaluate the different solutions?

- What do you see as the future of the real time insights in your company?
- What do you want to add to the areas we've touched upon?
- Would you like to add anything relevant which we haven't touched upon?

B.4.6. Interview questions v0.2

First I'd like to thank you for your participation in this interview. My name is Bob Warringa and I'm currently doing research to pursue my Master's degree at the Delft University of Technology. The goal of this research is to investigate how manufacturing SME's with legacy production assets can enable real-time insights into their component based production process. This is done by conducting interviews with industry experts with different roles the relevant organizations. I am excited to be able to speak to you and hear your input on the topic at hand. Please indicate if there are any unclear questions or needs for clarification.

B.4.7. Introduction

- What industry would you most associate your company with?
- What is your position within the company?
- What are your main responsibilities within the organization?
- What is your experience with real time monitoring of production assets? Production machines -
- How do you use the data gathered/generated/displayed by these processes?
- What do you think of the effect real time insights have on an organization?
- What do you think of the effect real time insights have on the individual employee?

B.4.8. Requirements and guidelines

- Could you describe the process of gaining insights in the production process in your company?
- How did you implement this process?
- Who are the stakeholders involved?
- Looking back, how would you rate the implementation of this process?
- What barriers were most prevalent in the implementation of this system?
- Are there areas of the production process that were hard to gain insights in?
- Are there areas of the production process that were easy to gain insights in?
- What would you see as the next step or part of the production process to gain insights into?
- What would need to be resolved or implemented before this could become a reality?

B.4.9. Benefit identification

- What is, in your opinion, the most crucial benefit of gaining real time insights into your production process?
- What is the effect of this benefit?
- Who are the stakeholders that benefit from this?
- How is this benefit used by the stakeholders?
- How does this influence the production process?
- How does this influence the organization?

B.4.10. Key features

- What are the most useful features that are built into the real time insights solution?
- How do you use these features?
- What effect do they have on your workflow?
- What features would you like to see in a future iteration?
- How would this impact your workflow?
- What features would you rate superfluous to the real time insights?
- Could you please state the reason for this?

B.4.11. Concluding

- What was the most impactful change needed in the company to implement real time insights?
- What were the key players involved in implementing the real time insights solution?
- What outside help did you need for the implementation of the solution?
- How did you evaluate the different solutions?
- What do you see as the future of the real time insights in your company?
- What do you want to add to the areas we’ve touched upon?
- Would you like to add anything relevant which we haven’t touched upon?

B.4.12. Interview questions v0.3

Introduction - First I'd like to thank you for your participation in this interview. My name is Bob Warringa and I'm currently doing research to pursue my Master's degree at the Delft University of Technology. The goal of this research is to investigate how manufacturing SME's with legacy production assets can enable real-time insights into their component based production process. This is done by conducting interviews with industry experts with different roles the relevant organizations. I am excited to be able to speak to you and hear your input on the topic at hand. Please indicate if there are any unclear questions or needs for clarification.

Q1 To start, can you tell me a bit about your background to help me understand your perspective?

Response: Input from interviewee, can be followed with related questions and answers.

Q2 - What is your view on the company's initiatives with regards to real time monitoring of production assets?

+ Why do you see it this way?
+ What types of initiatives did you observe?
+ What are the initiatives you feel are most impactful?
+ Why are these initiatives so impactful?

Q3 - Can you describe the process of implementing real time monitoring of production assets in your company? (SQ1)

+ What were the most important requirements to enable implementing this monitoring process?
+ Why were they so important?
+ Do you think this was well executed?

Q4 - What do you see as important requirements for other companies trying to implement real time monitoring? (SQ1)

+ Why are these requirements so important?
+ If they are well implemented, what are the benefits?
+ Which stakeholders are likely to be involved?

Q5 - What are the factors which are holding back real time insights in your company? (SQ1)

+ Why is that?
+ Who can influence these barriers?

Q6 - How do you see the benefits of real time insights impacting your organization?(SQ2)

+ What is the most important benefit?
+ Why is that?
+ Which stakeholder benefits the most from this?

Q7 - What do you see as the key features of gaining real time insights? (SQ3&4)

+ Why are these so important?
+ What effect do these have on your workflow?

[Design concept is shown and explained]

Q8 - What are your impressions of this proposed design concept? - (SQ4)

+ What do you think of the division of screens between different stakeholders?
+ What do you think is the most important information on the prototype?
+ What do you think is the least important information on the prototype?
+ What are you missing in this proposed design?

Q9 - Would you like to add something to our discussion or discuss a topic related to real time insights we have not touched upon?

Response: Possible unearthing of unknown issues and solution sets.

B.4.13. Interview questions v1.0

Introduction - First I'd like to thank you for your participation in this interview. My name is Bob Warringa and I'm currently doing research to pursue my Master's degree at the Delft University of Technology. The goal of this research is to investigate how manufacturing SME's with legacy production assets can enable real-time insights into their component based production process. This is done by conducting interviews with industry experts with different roles the relevant organizations. I am excited to be able to speak to you and hear your input on the topic at hand. Please indicate if there are any unclear questions or needs for clarification. The interview will take approximately 30 minutes.

Q1 To start, can you tell me a bit about your background to help me understand your perspective?

Response: Input from interviewee, can be followed with related questions and answers.

Q2 - What is your view on the company's initiatives with regards to real time monitoring of production assets?

+ Why do you see it this way?
+ What types of initiatives did you observe?
+ What are the initiatives you feel are most impactful?
+ Why are these initiatives so impactful?

Q3 - Can you describe the process of implementing real time monitoring of production assets in your company? (SQ1)

+ What were the most important requirements to enable implementing this monitoring process?
+ Why were they so important?
+ Do you think this was well executed?

Q4 - What do you see as important requirements for other companies trying to implement real time monitoring? (SQ1)

+ Why are these requirements so important?
+ If they are well implemented, what are the benefits?
+ Which stakeholders are likely to be involved?

Q5 - What are the factors which are holding back real time insights in your company? (SQ1)

+ Why is that?
+ Who can influence these barriers?

Q6 - How do you see the benefits of real time insights impacting your organization?(SQ2)

+ What is the most important benefit?
+ Why is that?
+ Which stakeholder benefits the most from this?

Q7 - What do you see as the key features of gaining real time insights? (SQ3&4)

- If interviewee is confused, provide examples: Spindle uptime, output visualisation, trialing performance, production planning etc.
+ Why are these so important?
+ What effect do these have on your workflow?

[Design concept is shown and explained]

Q8 - What are your impressions of this proposed design concept? - (SQ4)

+ What do you think of the division of screens between different stakeholders?
+ What do you think is the most important information on the prototype?
+ What do you think is the least important information on the prototype?
+ What are you missing in this proposed design?

Q9 - Would you like to add something to our discussion or discuss a topic related to real time insights we have not touched upon?

Response: Possible unearthing of unknown issues and solution sets.

B.5. Evaluation interview

B.5.1. Evaluation interview codes

ID	Name	Description
CE1	Q1: very negative	Interviewee responds very negative to Q1.
CE2	Q1: negative	Interviewee responds negative to Q1.
CE3	Q1: neutral	Interviewee responds neutral to Q1.
CE4	Q1: positive	Interviewee responds positive to Q1.
CE5	Q1: very positive	Interviewee responds very positive to Q1.
CE6	Q2: very negative	Interviewee responds very negative to Q2.
CE7	Q2: negative	Interviewee responds negative to Q2.
CE8	Q2: neutral	Interviewee responds neutral to Q2.
CE9	Q2: positive	Interviewee responds positive to Q2.
CE10	Q2: very positive	Interviewee responds very positive to Q2.
CE11	Q3: very negative	Interviewee responds very negative to Q3.
CE12	Q3: negative	Interviewee responds negative to Q3.
CE13	Q3: neutral	Interviewee responds neutral to Q3.
CE14	Q3: positive	Interviewee responds positive to Q3.
CE15	Q3: very positive	Interviewee responds very positive to Q3.
CE16	Q4: very negative	Interviewee responds very negative to Q4.
CE17	Q4: negative	Interviewee responds negative to Q4.
CE18	Q4: neutral	Interviewee responds neutral to Q4.
CE19	Q4: positive	Interviewee responds positive to Q4.
CE20	Q4: very positive	Interviewee responds very positive to Q4.

CE21	Q5: very negative	Interviewee responds very negative to Q5.
CE22	Q5: negative	Interviewee responds negative to Q5.
CE23	Q5: neutral	Interviewee responds neutral to Q5.
CE24	Q5: positive	Interviewee responds positive to Q5.
CE25	Q5: very positive	Interviewee responds very positive to Q5.
CE26	Q6: very negative	Interviewee responds very negative to Q6.
CE27	Q6: negative	Interviewee responds negative to Q6.
CE28	Q6: neutral	Interviewee responds neutral to Q6.
CE29	Q6: positive	Interviewee responds positive to Q6.
CE30	Q6: very positive	Interviewee responds very positive to Q6.
CE31	Q7: very negative	Interviewee responds very negative to Q7.
CE32	Q7: negative	Interviewee responds negative to Q7.
CE33	Q7: neutral	Interviewee responds neutral to Q7.
CE34	Q7: positive	Interviewee responds positive to Q7.
CE35	Q7: very positive	Interviewee responds very positive to Q7.
CE36	Q8: very negative	Interviewee responds very negative to Q8.
CE37	Q8: negative	Interviewee responds negative to Q8.
CE38	Q8: neutral	Interviewee responds neutral to Q8.
CE39	Q8: positive	Interviewee responds positive to Q8.
CE40	Q8: very positive	Interviewee responds very positive to Q8.
CE41	Q9: very negative	Interviewee responds very negative to Q9.
CE42	Q9: negative	Interviewee responds negative to Q9.
CE43	Q9: neutral	Interviewee responds neutral to Q9.
CE44	Q9: positive	Interviewee responds positive to Q9.
CE45	Q9: very positive	Interviewee responds very positive to Q9.
CE46	Q10: very negative	Interviewee responds very negative to Q10.
CE47	Q10: negative	Interviewee responds negative to Q10.
CE48	Q10: neutral	Interviewee responds neutral to Q10.
CE49	Q10: positive	Interviewee responds positive to Q10.
CE50	Q10: very positive	Interviewee responds very positive to Q10.
CE51	Q11: very negative	Interviewee responds very negative to Q11.
CE52	Q11: negative	Interviewee responds negative to Q11.
CE53	Q11: neutral	Interviewee responds neutral to Q11.
CE54	Q11: positive	Interviewee responds positive to Q11.
CE55	Q11: very positive	Interviewee responds very positive to Q11.
CE56	Q12: differentiation	Interviewee indicates that they find it important that the KPIs are different per machine and need to be evaluated individually in order to have effective evaluation.

B.5.2. Evaluation interview guide

- Show the interview participant a high level overview of the proposed design. Explain different components of the design and what they are based on.
- Show the interview participant a focused view of individual components of the prototype and the relations between the different design aspects.
- Show the interview participant how the KPI development came to be and how the different factors relate to eachother.

Q1 Do you agree with the general concept of real time insights?

Q2 Do you think the most crucial requirements are met for gaining real time insights?

Q3 Do you think that the most crucial benefit of real time insights is clear to the end-user?

Q4 Do you think that the key features needed for real time insights are present in the prototype?

Q5 Do you think the proposed design will improve the communication within a company?

Q6 Do you think the proposed design will improve the production process within a company?

Q7 Do you think the proposed design will improve the productivity within a company?

Q8 Do you think the KPI development was done with the right assumptions and standards?

Q9 Do you think the central KPI gives enough context to the production process?

Q10 Do you think the central KPI gives enough information to evaluate the performance of the production process?

Q11 Do you think such a system could be implemented within a reasonable time frame in a small and medium-sized enterprise?

Q12 - Do you have any additional feedback on the prototype or the KPI development, we've not yet touched upon?

B.5.3. Evaluation results

In the right most column of the resulting Tables B.5 and B.6, the scores are aggregated on a scale from 1 to one hundred for simple ranking and evaluation. Keep in mind that a uniformly neutral response would result in a score amounting to sixty. In order to evaluate the negative or positive coding related to the interview, a score below 70 is considered weak; a majority of respondents are negative or neutral to the posed question.

Question	–	-	0	+	++	**Score**
Q1: General concept of real time insights	0	0	0	1	2	93
Q2: Meeting crucial requirements	0	0	0	2	1	87
Q3: Benefits of real time insights	0	0	0	1	2	93
Q4: Key features present	0	0	0	2	1	87
Q5: Improving communications	0	0	1	1	1	80
Q6: Improving production efficiency	0	0	0	3	0	80
Q7: Improving productivity	0	0	0	3	0	80

Table B.5: Results of evaluating the concept and design.

Question	–	-	0	+	++	**Score**
Q8: KPI development	0	0	1	2	0	73
Q9: KPI context	0	0	1	1	1	80
Q10: KPI evaluation	0	0	1	2	0	73
Q11: Implementation of prototype	0	0	0	2	1	87

Table B.6: Results of evaluating the indicators and implementation.

C

Appendix C - Design prototypes

In this section, the design prototypes are presented again, in double the size. Please refer to Chapter 5 for context on design choices.

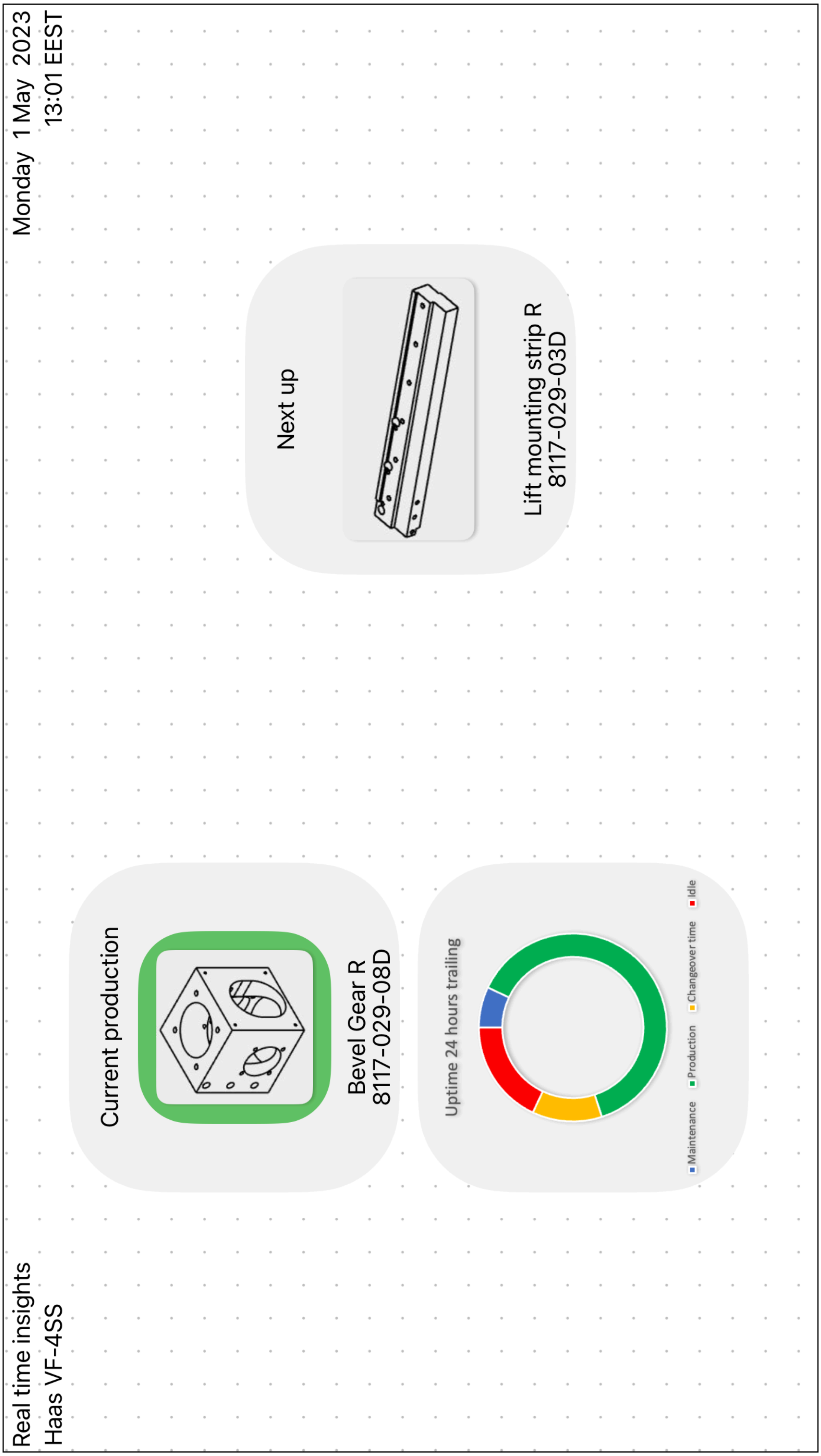

Figure C.1: Real time insights prototype - operator view

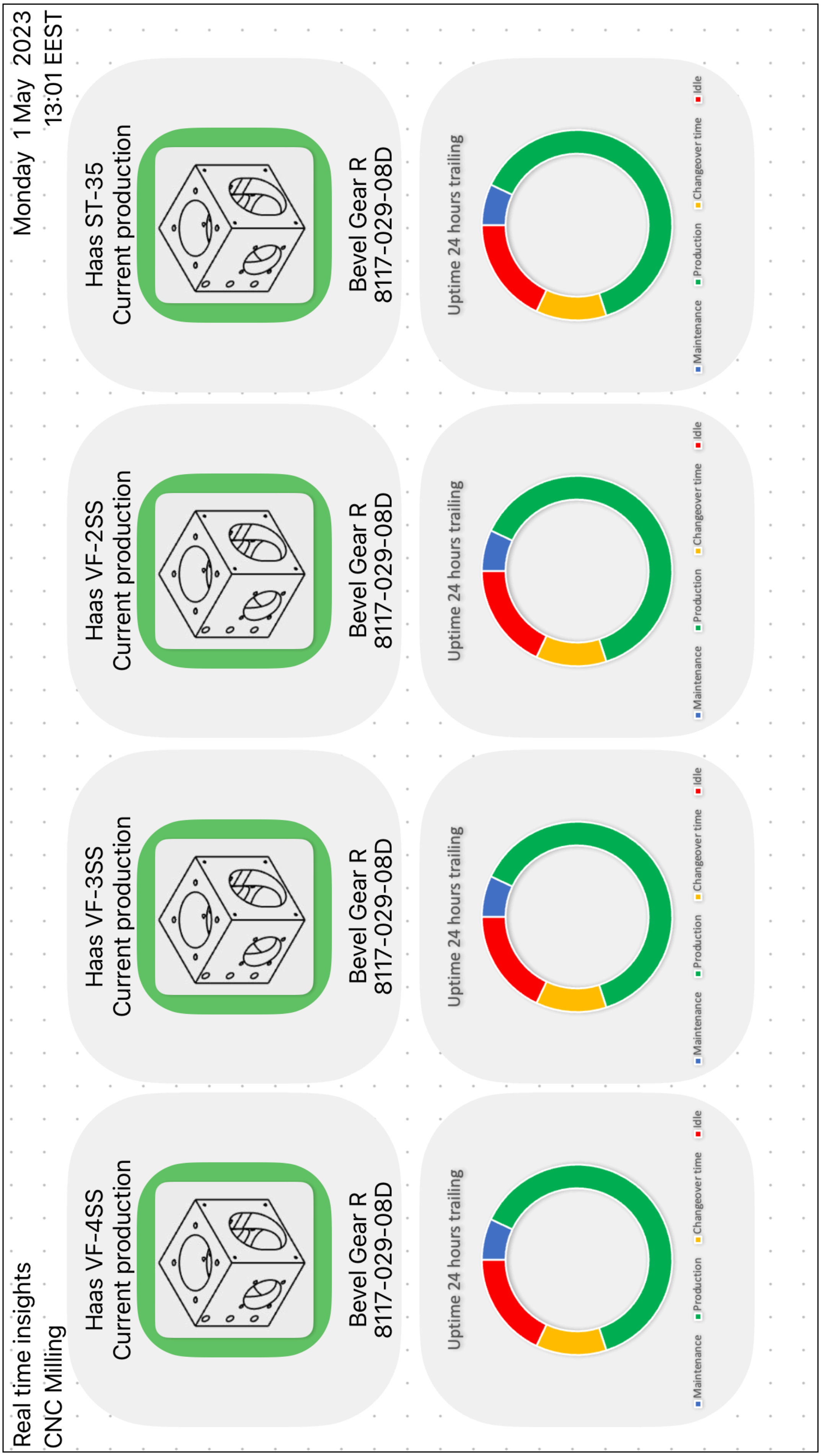

Figure C.2: Real time insights prototype - foreman view

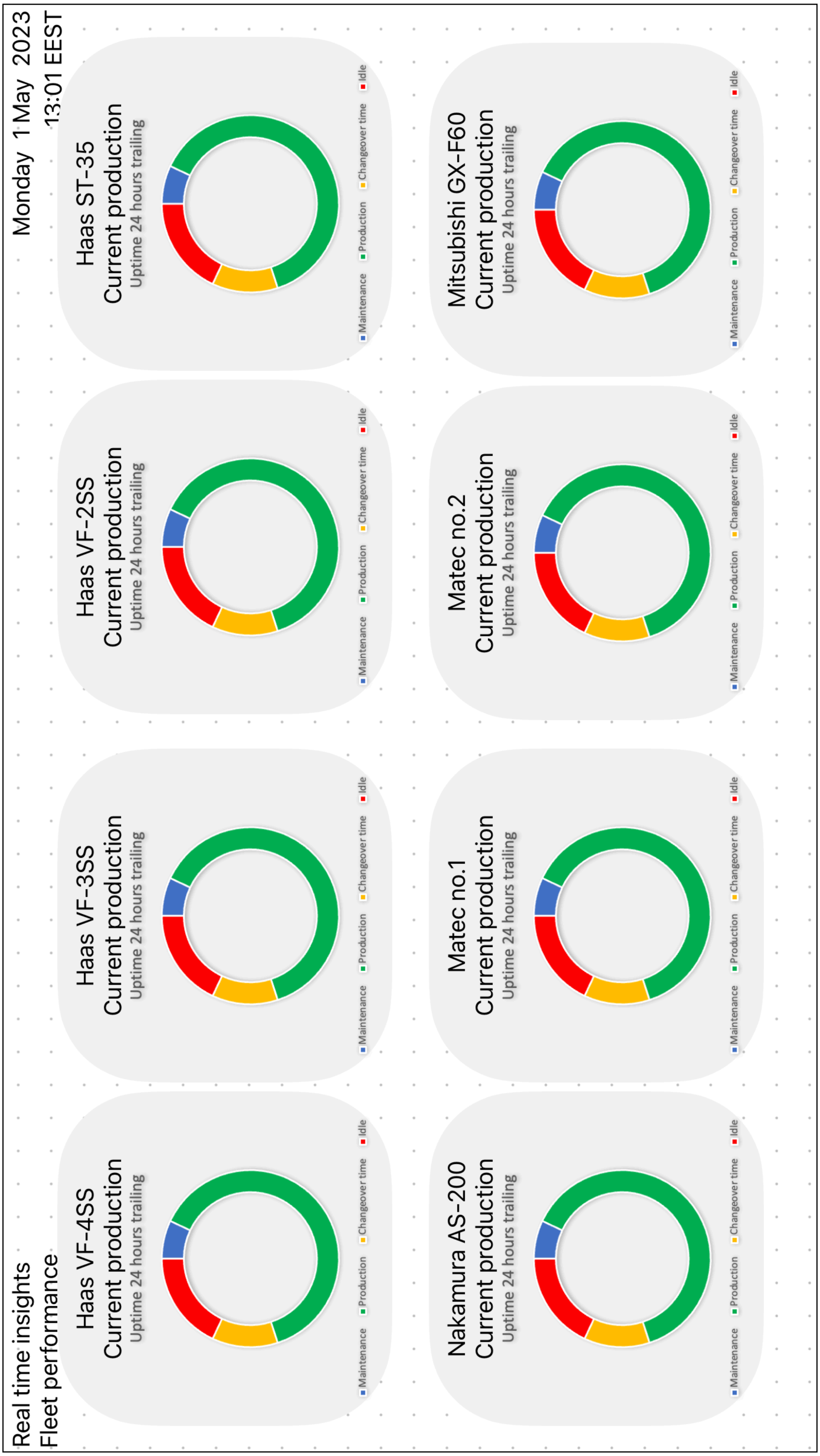

Figure C.3: Real time insights prototype - management view

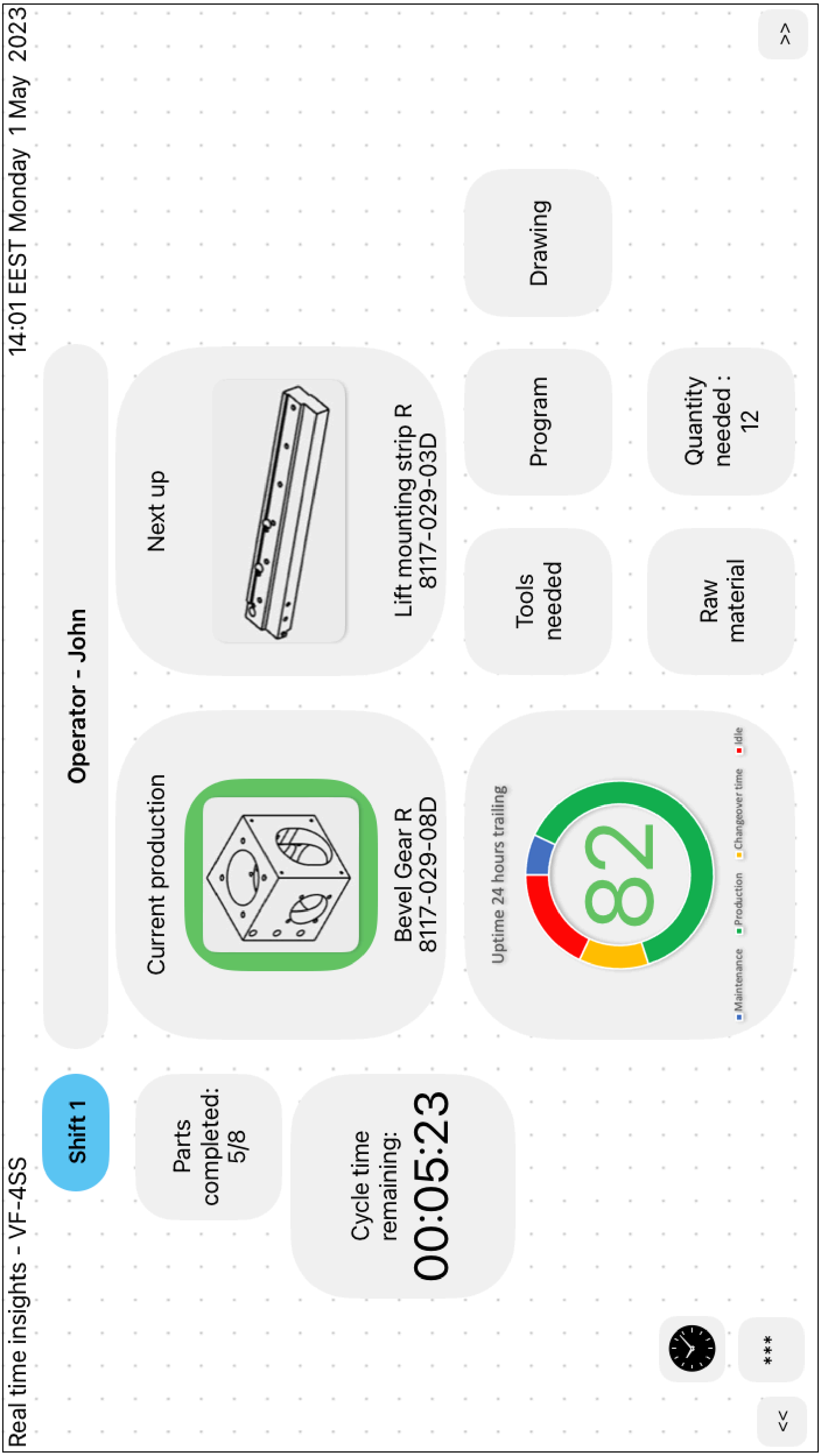

Figure C.4: Design prototype 2 - Screen 1

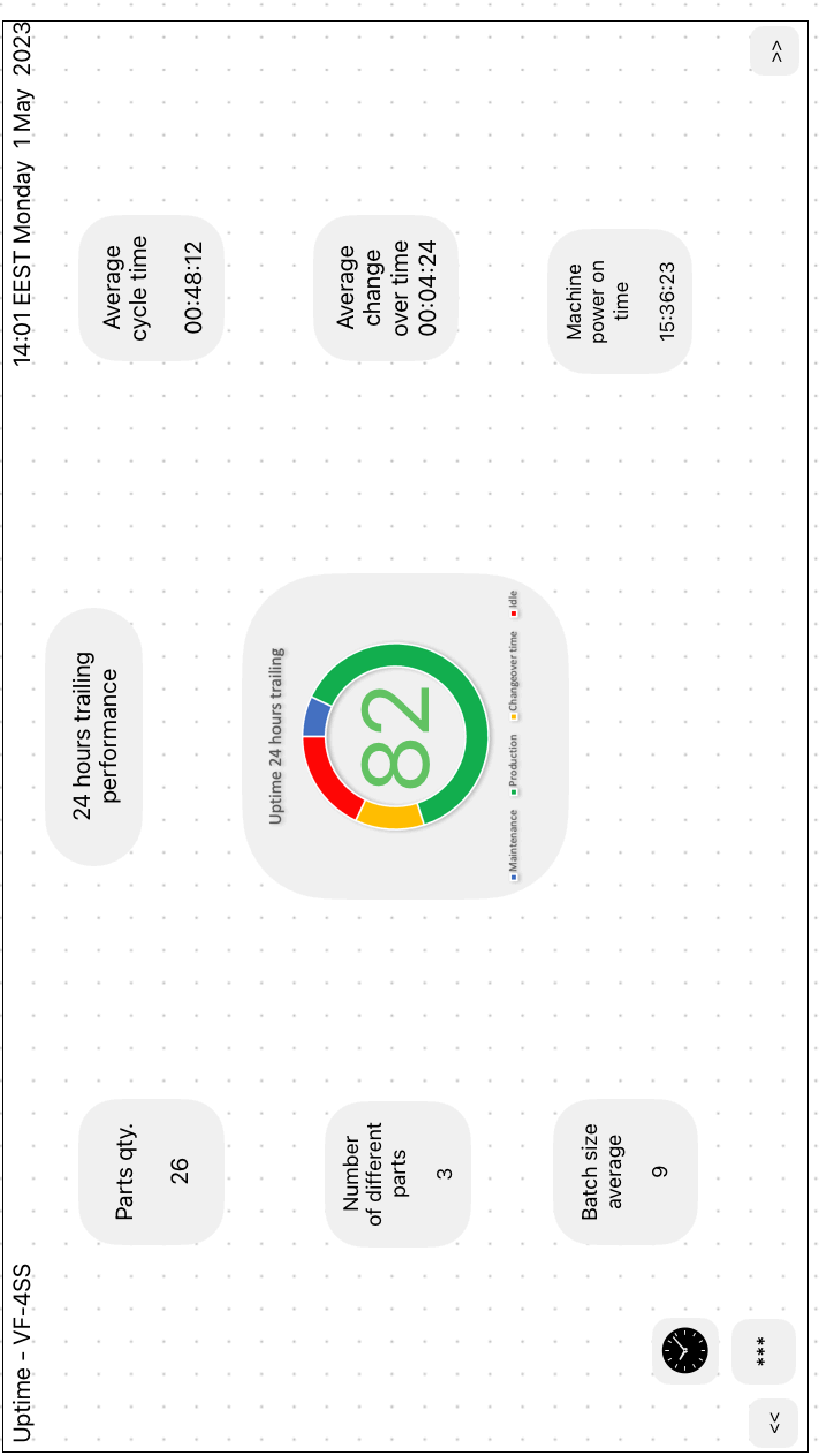

Figure C.5: Design prototype 2 - Screen 2

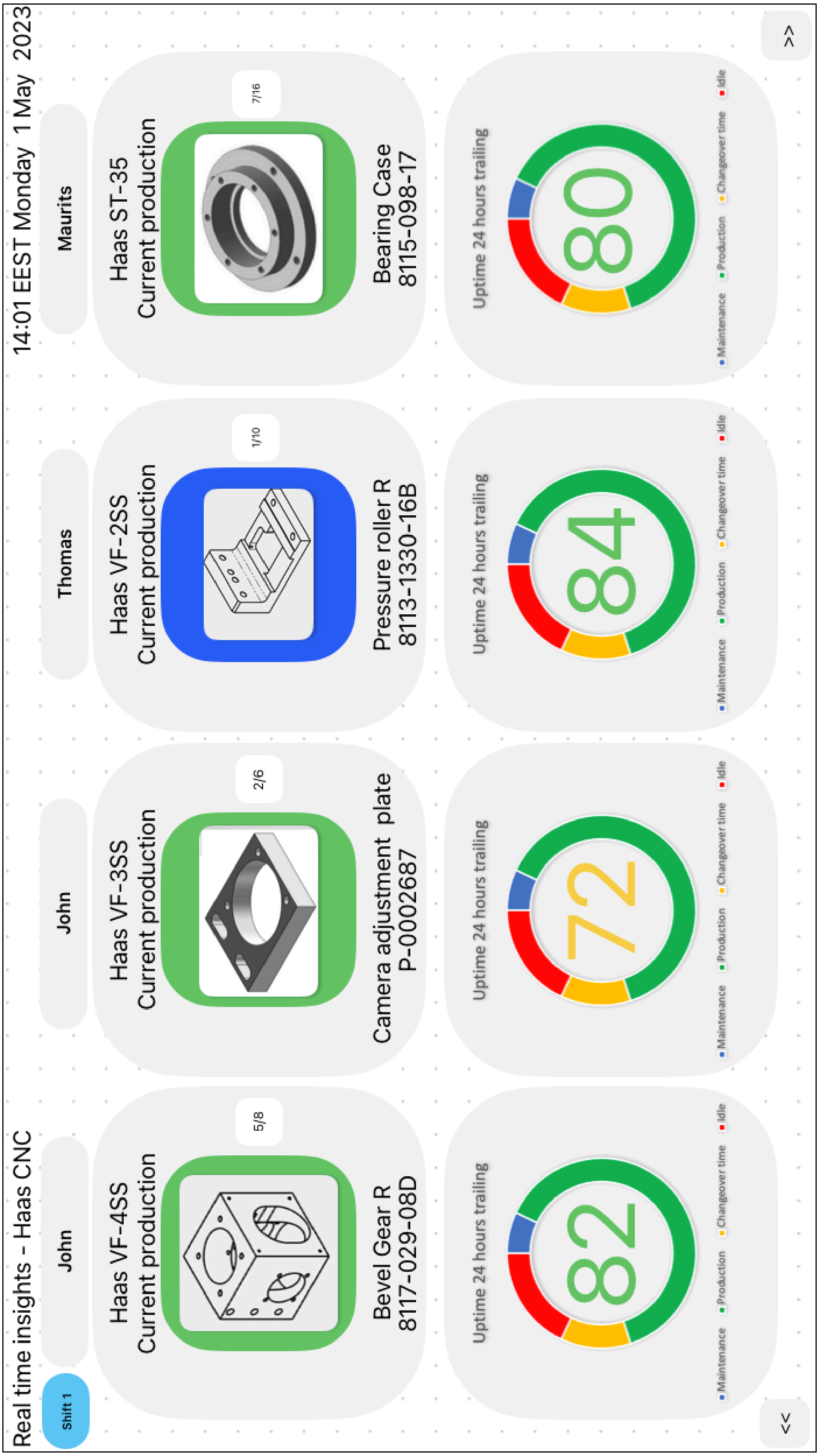

Figure C.6: Design prototype 2- Screen 3

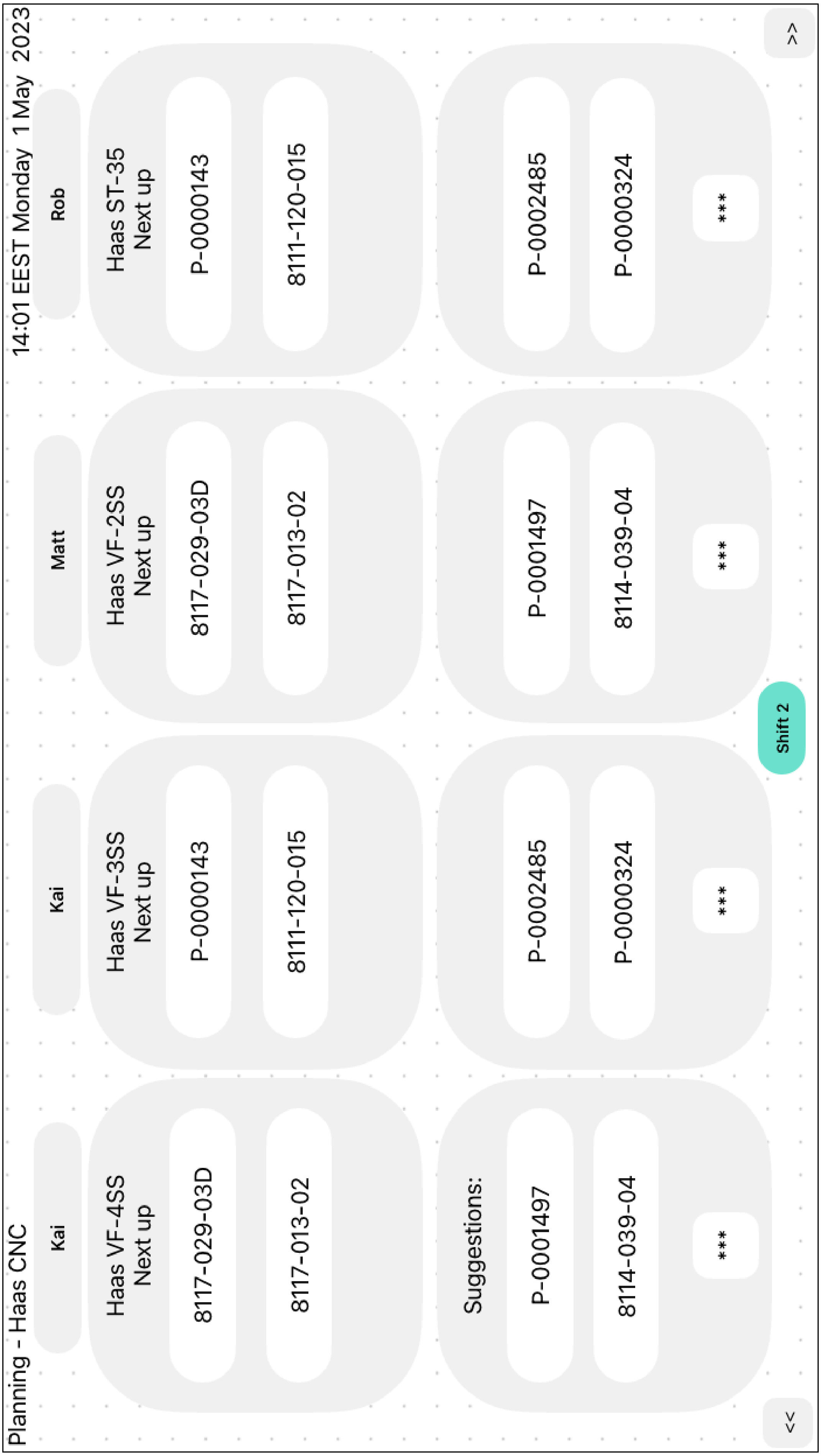

Figure C.7: Design prototype 2 - Screen 4

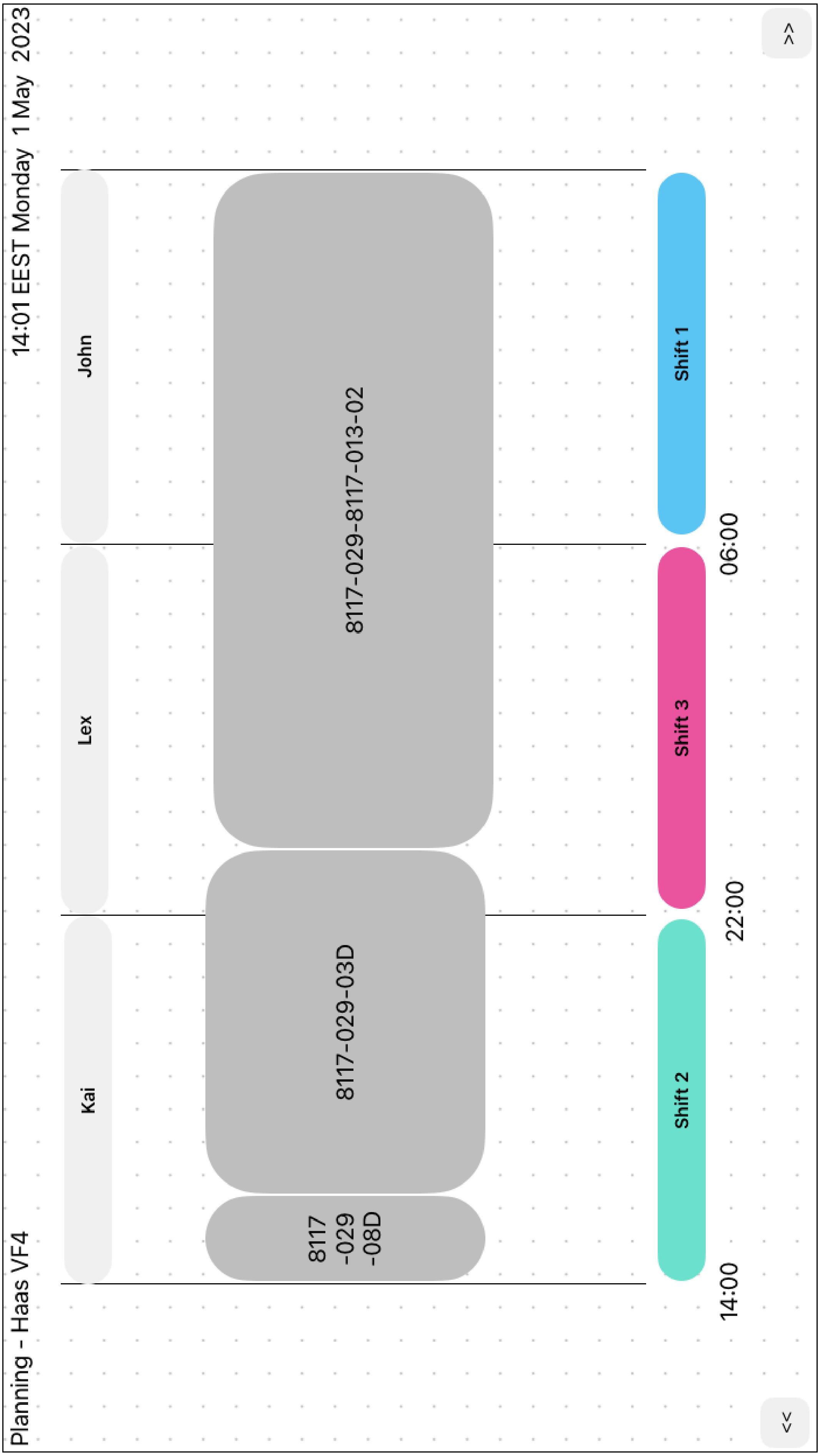

Figure C.8: Design prototype 2 - Screen 5

Figure C.9: Design prototype 2 - Screen 6

D

Appendix D - Coding instructions for a basic interface

In this appendix, a very rudimentary functional version of code is given to extract machine data from a written data source on a computer and present a visual interface of the 24 hour trailing manufacturing data. This prototype was made in Visual Studio Code.

```
    Create a new Windows Forms application in Visual Studio.
    Drag a Panel control onto the form and set its Dock property to Fill.
    In the Form_Load event, create a Timer control that will update the timeline every minute,
    and start it. For example:

csharp

private void Form1_Load(object sender, EventArgs e)
{
    Timer timer = new Timer();
    timer.Interval = 60000; // update every minute
    timer.Tick += Timer_Tick;
    timer.Start();
}

    In the Timer_Tick event, query the server for the machine's uptime status for
    the past 24 hours and update the timeline accordingly. For example:

scss

private void Timer_Tick(object sender, EventArgs e)
{
    DateTime now = DateTime.Now;
    DateTime startDate = now.AddDays(-1);

    // query server for uptime status for past 24 hours
    // assuming the server returns an array of bool values
    bool[] uptimeStatus = QueryServerForUptimeStatus(startDate, now);

    // clear the panel
    panel1.Controls.Clear();
```

```
    // calculate the width of each timeline block based on the panel width and number
    of blocks
    int blockWidth = panel1.Width / uptimeStatus.Length;

    // iterate over the uptime status array and create a timeline block for each minute
    for (int i = 0; i < uptimeStatus.Length; i++)
    {
        DateTime blockStart = startDate.AddMinutes(i);
        DateTime blockEnd = blockStart.AddMinutes(1);

        // create a new timeline block control
        Control block = new Control();
        block.BackColor = uptimeStatus[i] ? Color.Green : Color.Red;
        block.Width = blockWidth;
        block.Height = panel1.Height;
        block.Left = i * blockWidth;
        block.Top = 0;
        block.Tag = blockStart; // store the start time of the block in the control's
        Tag property
        block.Click += Block_Click;

        // add the block to the panel
        panel1.Controls.Add(block);
    }
}
```

    In the Block_Click event, display the uptime status for the selected block in a
    MessageBox. For example:

csharp

```
private void Block_Click(object sender, EventArgs e)
{
    Control block = sender as Control;
    DateTime blockStart = (DateTime)block.Tag;
    DateTime blockEnd = blockStart.AddMinutes(1);

    // query server for uptime status for the selected block
    bool blockUptimeStatus = QueryServerForUptimeStatus(blockStart, blockEnd)[0];

    // display the uptime status in a MessageBox
    MessageBox.Show(string.Format("Uptime status for {0} - {1}: {2}", blockStart, blockEnd,
    blockUptimeStatus ? "UP" : "DOWN"));
}
```

csharp

```
private bool[] QueryServerForUptimeStatus(DateTime start, DateTime end)
{
    // make HTTP request to server API to get uptime status data
    // assuming the API returns an array of bool values
    string apiUrl = "http://example.com/api/uptime?start=" + start.ToString("yyyy-MM-dd HH:mm:ss") +
    string response = MakeHttpRequest(apiUrl);
```

```
    // parse the response and return the uptime status array
    bool[] uptimeStatus = ParseUptimeStatusFrom
```

----

scss

```
private void timer1_Tick(object sender, EventArgs e)
{
    // update the machine information for each tab
    UpdateIndividualMachinesTab();
    UpdateOverviewTab();
    UpdateGeneralTab();
}
```

    Implement the UpdateIndividualMachinesTab method to update the DataGridView control on the "Indi

scss

```
private void UpdateIndividualMachinesTab()
{
    // get the machine information for each individual machine
    foreach (DataGridViewRow row in dataGridViewIndividualMachines.Rows)
    {
        string machineName = (string)row.Cells["MachineName"].Value;
        string apiUrl = string.Format("http://example.com/api/machines/{0}", machineName);
        string response = MakeHttpRequest(apiUrl);

        // parse the response to get the machine information
        // ...

        // update the row cells with the machine information
        row.Cells["Uptime"].Value = uptime;
        row.Cells["CurrentPart"].Value = currentPart;
        row.Cells["NextPart"].Value = nextPart;
        row.Cells["SpindleUptime"].Value = spindleUptime;
        row.Cells["OperatorPerformance"].Value = operatorPerformance;
        row.Cells["TimeToMaintenance"].Value = timeToMaintenance;
    }
}
```

scss

```
private void UpdateOverviewTab()
{
    // get the machine information for each machine
    foreach (DataGridViewRow row in dataGridViewOverview.Rows)
    {
        string machineName = (string)row.Cells["MachineName"].Value;
        string apiUrl = string.Format("http://example.com/api/machines/{0}", machineName);
        string response = MakeHttpRequest(apiUrl);
```

```
    // parse the response to get the machine information
    // ...

    // update the row cells with the machine information
    row.Cells["Uptime"].Value = uptime;
    row.Cells["OperatorPerformance"].Value = operatorPerformance;
    row.Cells["TimeToMaintenance"].Value = timeToMaintenance;
}

// update the fleet uptime and timeline of uptime
TimeSpan fleetUptime = TimeSpan.Zero;
DataTable timelineTable = dataGridViewTimeline.DataSource as DataTable;
timelineTable.Rows.Clear();

foreach (DataGridViewRow row in dataGridViewOverview.Rows)
{
    TimeSpan machineUptime = (TimeSpan)row.Cells["Uptime"].Value;
    fleetUptime += machineUptime;

    // add a row to the timeline table for this machine's uptime
    timelineTable.Rows.Add(row.Cells["MachineName"].Value, machineUptime);
}

lblFleetUptimeValue.Text = string.Format("{0:%d} days {0:%h} hours {0:%m}
```

E

Appendix E - Informed consent

This appendix contains the informed consent form, required by the HREC of the Delft University of Technology.

Gaining real time insights into SME manufacturing: implementation of Industry 4.0 technologies with legacy assets

Bob Warringa
Management of Technology
Delft University of Technology
b.j.j.j.warringa@student.tudelft.nl

You are being invited to participate in a research study titled: Gaining real time insights into SME manufacturing: implementation of Industry 4.0 technologies with legacy assets. This study is being done by Bob Warringa from the TU Delft under supervision of Dr. Aaron Ding. This research is being done in association with Color Control Group B.V.

The purpose of this research study is to identify gains from utilizing real time data in small and medium sized manufacturing companies, and will take you approximately 30 minutes to complete. The data will be used for problem identification, concept creation and solution set generation. We will be asking you to provide views on concepts, solutions and identify features most critical to the research.

As with any online activity the risk of a breach is always possible. To the best of our ability your answers in this study will remain confidential. We will minimize any risks by anonymizing the data after collection and ensuring destruction of raw data after processing. Anonymized data will be securely stored and encrypted.

Your participation in this study is entirely voluntary and you can withdraw at any time. You are free to omit any questions. Data gathered in this research will be destroyed by 01/09/2023.

Contact:
Bob Warringa
b.j.j.j.warringa@student.tudelft.nl

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
A: GENERAL AGREEMENT – RESEARCH GOALS, PARTICPANT TASKS AND VOLUNTARY PARTICIPATION		
1. I have read and understood the information above, or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	☐	☐
2. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	☐	☐
3. I understand that taking part in the study involves: taking part in an audio-recorded interview, transcribed into written data points. Afterwards the recording will be destroyed and written summary will be provided to me for feedback	☐	☐
B: POTENTIAL RISKS OF PARTICIPATING (INCLUDING DATA PROTECTION)		
1. I understand that taking part in the study involves the following risks: Covid infection. I understand that these will be mitigated by taking into account government-mandated transmission guidelines.	☐	☐

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
2. I understand that taking part in the study also involves collecting specific personally identifiable information (PII) [Name] and associated personally identifiable research data (PIRD) [Role] with the potential risk of my identity being revealed.	☐	☐
3. I understand that the following steps will be taken to minimise the threat of a data breach, and protect my identity in the event of such a breach by anonymization of data and aggregation.	☐	☐
4. I understand that personal information collected about me that can identify me, will not be shared beyond the study team.	☐	☐
C: RESEARCH PUBLICATION, DISSEMINATION AND APPLICATION		
1. I understand that after the research study the summarized answers I provide will be used for the Master's Thesis and eventual publication.	☐	☐
D: DATA STORAGE, ACCESS AND REUSE		
1. I give permission for the resulting summary that to be archived in TU Delft repository so it can be used for future research and learning.	☐	☐

Signatures

________________________ ________________________ __________

Name of participant | Signature | Date

I, as researcher, have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

Bob Warringa **11/04/2023**

________________________ ________________________ __________

Researcher name | Signature | Date

Study contact details for further information:

Bob Warringa

bobwarringa@gmail.com

+31681637451