The design of a roadmap for the integration of remote support into a production environment

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Tembo UNIVERSITY OF TWENTE.

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Preface

During my study programme, I came to the realisation how much I enjoy introducing new technologies to people. Bringing that 'wow'-factor is what gives me joy. I have experienced this with 3D printing, but also with Virtual- and Augmented Reality. I genuinely believe that these technologies, which are still considered gimmicks by many, are currently at a turning point to becoming useful for everyday use. We see technology rapidly advancing around us, and we can imagine what we are able to achieve if we put these technologies to good use.

To conclude the master's programme of Industrial Design Engineering at the University of Twente, an individual project was externally carried out at Tembo Group B.V. This project is described in this thesis and is meant to show my abilities as both a designer and a researcher. The project is meant to reflect and implement the knowledge gained during the master's programme, but also provided me with the opportunity to gain new knowledge during this final part of my study.

I would like to thank Tembo, for sharing the vision that incorporating new technologies should be the way forward. They have provided me with valuable insights into the production process, and have showed to be open to new insights from students like myself. On top of that, I have particularly enjoyed working with people of many nationalities, especially during the user tests I was allowed to conduct in Spain.

A special thank you goes out to Maaike Slot, for patiently guiding me in the process of writing a thesis and taking the time to give valuable feedback time and again. I also want to thank my friends and family for sharing my enthusiasm for the project during the good times and helping me push through the tough times.
I hope you enjoy reading my thesis!

Lucas Pronk
January 20th, 2023

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Abstract

This thesis looks into the usage of remote support for problem identification and problem solving of malfunctioning production machines. This is necessary because support staff currently has to travel, often by plane, to customers for maintenance. This way of support takes a lot of time and money and is not a sustainable solution moving forwards. On top of that, the transition to a performance-based business model increases the motivation for a remote alternative. Therefore, to help original equipment manufacturers, this thesis shows how different Industry 4.0 technologies can enable remote support. More specifically, Extended Reality, Digital Twinning, Human-machine Interaction and Product Lifecycle Management were chosen as the key enablers for remote support. To assist industry in enabling remote support with these Industry 4.0 technologies, a roadmap is designed.

A roadmap is created for this thesis to assist industry in its efforts to incorporate a new tool, such as remote support, in their current practices. This is done by aligning the strategy and vision of original equipment manufacturers with technological developments and defining a use case based on their strategy. The roadmap also aids original equipment manufacturers in translating the vision and action plan to their customers, since a use case such as remote support requires the two parties to be aligned. The roadmap is verified and validated through a case study.

Abbreviations

2D	Two-dimensional
3D	Three-dimensional
AR	Augmented Reality
AV	Augmented Virtuality
CAD	Computer-aided design
DSR	Digital System Reference
HMD	Head-mounted display
HMI	Human-machine interaction
MR	Mixed Reality
OEE	Overall equipment effectiveness
OEM	Original equipment manufacturer
PLM	Product lifecycle management
RAMI4.0	Reference architecture model for Industry 4.0
VR	Virtual Reality
XR	Extended Reality

1. Introduction

In this chapter, the foundations are laid out for the rest of this thesis. First, the problem this assignment attempts to solve is explained, together with the business model that supports it. The proposed solution to the problem, remote support, will then be assessed. Lastly, the research questions, methodology and scope are defined.

1.1. Problem definition

Maintaining machines worldwide can be a complex, time-consuming and expensive task for companies in the production industry. If a production company is not the original equipment manufacturer (OEM) of the machines that they use, they usually depend on the company, often the OEM, which the machines are bought from. These companies that buy the machines for their own production are further referred to as 'customers'.

Production machines today are complex machines with a lot of moving parts. Therefore, the number of different defects that may occur can be substantial, and downtime of these machines is inevitable and occurs often. Moreover, since the machines are complex and built from many different components, it is often unclear which parts need to be replaced in case of a defect or malfunction. The customers have knowledge of how to run production with the machines but often only have basic knowledge of the machines themselves. This basic knowledge is often insufficient to successfully detect malfunctioning parts. Currently, when a machine malfunctions or breaks down, supporting staff of the OEM must travel to the customer to inspect the defects of the machines, travel back to pick up the correct replacement parts, and once again travel to the customer for the actual repair. It is common for OEMs and their customers to be in different countries, so travelling often occurs by plane. Production machines can be complex and break down often, making this a time-consuming and resource-intensive task. On top of this, travelling this much for repair jobs is not economically or environmentally sustainable and thus is a significant motivator to find alternative solutions.

1.2. Performance-based business model

Besides the aforementioned problem, there is also an increased interest in delivering value to the customer instead of just a physical product. This section elaborates on the performance-based business model, which is essential for understanding the rest of this report. Value-adding services are, for example, combining the physical product and the maintenance as one service [1]. While previously, the business model for repair and maintenance was often based on time and material contracts. As a replacement for the time and material-based business model, a performance-based business model was introduced and is increasing in popularity [2]. In this new business model, the incentives of the OEM and their customers are the same, as shown in Figure 1.

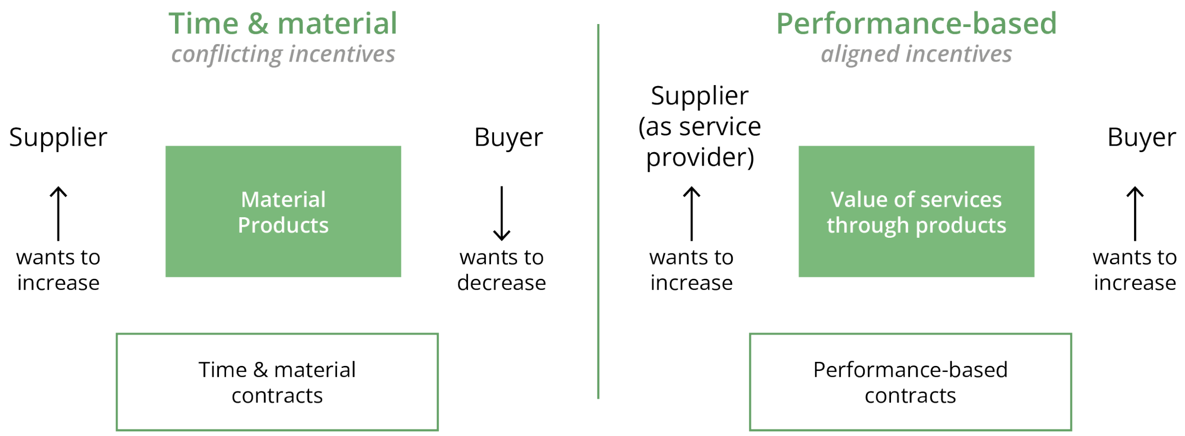

Figure 1: Incentive alignment based on the business model [2]

The transition of industrial companies to become digital factories is an enabler in adopting a performance-based business model. This push shifts the focus for OEMs from what products and services to offer customers to what the value is to the customer of these provided products and services [1]. This value is based on the customer's needs, which is to produce as much as possible with the machines they buy. With the performance-based business model, there is a shared responsibility between the OEMs and customers to keep the machine running. Offering services to the customers that create a better understanding of the machines will increase the added value to the customer, as they are able to lower the downtime of the machines.

At its core, the performance-based business model aligns with the incentives of the OEM and their customers. Before, OEMs had a financial incentive to sell as many machines, products or services as possible for the highest price their customers would accept. Contrary to this, customers wanted to buy as few machines, products and services as possible for the lowest price.
By adopting a performance-based model, the OEM is no longer paid per machine. Instead, they are paid based on the predicted output of the machine. If the machine at the customer produces more products than expected, the machine OEM gets a larger share of the profit. In the same way, the machine OEM gets less, or even nothing at all, if the machines produce less than expected.

This margin is calculated based on the overall equipment effectiveness (OEE) of the machine. The OEE is a means to define the effectiveness of a production machine, and it is calculated based on three different variables: availability, performance, and quality [3]. Availability is defined as the percentage of time the machine was able to operate compared to the maximum available operation time, performance is the percentage of the actual speed compared to the maximum possible speed, and quality is the percentage of accepted products compared to the maximum number of products that could have been produced. The formula for calculating OEE is as follows and visualised in Figure 2:

$$OEE = Availability * Performance * Quality = \frac{B}{A} * \frac{D}{C} * \frac{F}{E}$$

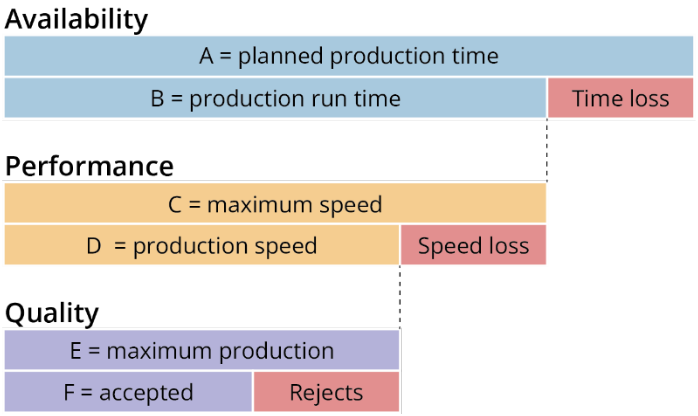

Figure 2: Visualisation of OEE calculation

The production time is the time in which the machine is in a running state and in production. The time loss is the time in which production was planned, and the machine was intended to be running but was not running. This can be caused by several things: machine start-up, unplanned stops (e.g., machine failure), or planned stops (e.g., change of machine parts). Not included in the time loss are scheduled stops (e.g., breaks, plant shut down). Planned stops are needed to get the machine running, while with scheduled stops, there is no intention of running the machines. The speed loss is the loss of performance. It is any production time when the machine is not at its maximum manufacturing speed. This can be caused by slow runs (e.g., testing the machine after a failure), idling and small stops. Here, small stops are brief pauses in the production where their duration is too small to be tracked as a machine failure. On most modern machines, there are several checkpoints where cameras and other sensors are placed to check for the quality of the product. If the product is detected to not meet the quality standards, it is rejected. Products that do not meet the quality standards but were not rejected by the machine still account for accepted parts.

The three variables of the OEE calculation (availability, performance and quality) each have two main contributors to the OEE loss, as is shown in Figure 3. One of the proposed solutions to address these contributors is remote support. Remote support will enable supporting staff to help customers from a distance, removing the need to go to the customer physically. If this reduces (the effect of) one or multiple of the six contributors, this will increase the OEE of the machines. This makes remote support beneficial for both the production companies and their customers. Besides the improvement of OEE, remote support will also reduce the environmental impact of detecting and solving machine problems.

Overall equipment effectiveness variable	Six big losses
Availability (Time loss)	Unplanned stops
	Planned stops
Performance (Speed loss)	Small stops
	Slow cycles
Quality (Rejects)	Production rejects
	Startup rejects

Figure 3: Six big losses in OEE, adapted from [4]

Remote support could have the most significant impact on the availability, as it is meant to solve equipment failures more quickly and helps with setting up and restarting the production. This decrease in downtime makes remote support beneficial for both production companies and their customers.

Therefore, production companies that implement the performance-based business model, using the OEE calculation as a basis, could benefit from remote support. Remote support is further elaborated on in the next chapter to understand how companies can benefit from remote support.

1.3. Remote support

With the complexity of today's machines, fully understanding the process and defects during production failure can be a difficult task. Remote support, as the name suggests, aims to help the on-site worker identify or solve the problem from a distant location. At its core, remote support aims to transfer the knowledge and information to the location of the problem instead of moving the carrier of this knowledge and information to that location. Remote support can be characterised by three criteria [5]:

- Geographical distance: the physical distance between the on-site worker and the remote expert.
- Use of information technology: all the technologies used to transfer and process the knowledge and information from the remote expert to the on-site worker.
- Industrial service: the kind of services that remote support is intended to enhance. This involves identifying or solving a mechanical failure and assisting in cleaning the machine or other industrial processes.

These three criteria are useful to define remote support. Without these criteria, standing a few meters apart while helping each other could technically also be defined as remote support. Remote support, according to these three criteria, was first possible with telecommunication. With vocal assistance, people could help each other with the knowledge they had that the person on the other side of the line did not have. This form of remote support, even if it is not called remote support, is still widely used in both professional and private settings. This works well for simple problems with easy solutions, but they often fail with more complex problems.

Nowadays, it is common for an industrial company to have its own (internal) IT helpdesk. As with remote support, simple problems are often resolved with communicational tools such as email and phone calls. When this is insufficient to solve the issue, it is the easiest and least time-consuming to let the expert, in this case, the IT helpdesk, solve the problem for you. However, sometimes it is not possible for the person having an issue to go to the helpdesk physically. In this case, remote support tools are available to share the screen with the expert or even let them take control completely, with the goal of solving the issue as fast as possible. These solutions work well for IT-related problems when they are software related since the issues are often not complex and can be solved by simply changing some software settings. Industrial companies and their customers face a different challenge, as the problems with production machines that require local assistance are mostly hardware related. Therefore, a solution needs to be found where a remote expert is still able to successfully assist on-site workers, independent of their knowledge. A storyboard of the evolution of these remote support practices is shown in Figure 4, with the current practices being calling, emailing and remote control.

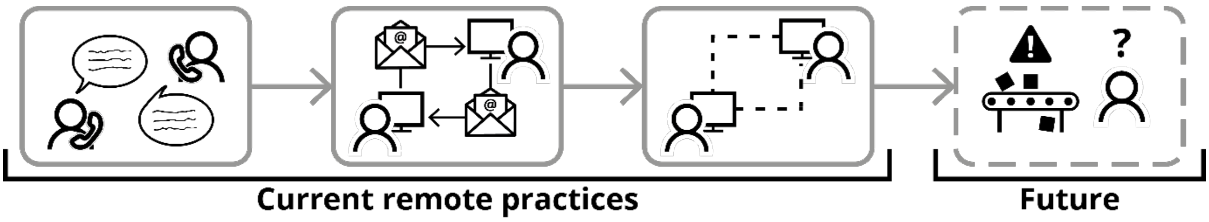

Figure 4: Storyboard of the remote support practices

Besides the difference between software and hardware issues, there is also a linearity between the complexity of the problem and the complexity of the tools required to solve the problem, as is visualised in Figure 5. This visualisation is based on the flow theory [6]. In the case of remote support in industry, more complex tools are required to solve complex machine problems. However, if the problems are easy to fix, employees may be less inclined to use these complex tools. There is a fine line where the complexity of the tool meets the complexity of the problem. In this case, this will be the optimal way to solve an issue. If the tool is more complex than the problem at hand, it can be experienced as a tool that is too time-consuming. On the other hand, if the problem is more complex than the communicational tools, the knowledge needed to solve the problem might not be transferred successfully.

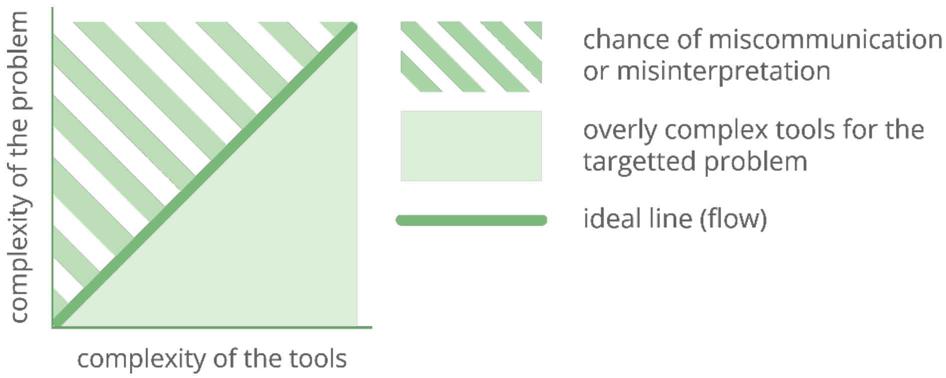

Figure 5: Simplified visualisation of complexity of the problem versus tool

The problems that occur on the machines can be complex. On top of that, there are a lot of possible misunderstandings when trying to solve an issue remotely. The customer can lack the knowledge required to explain the issue to the remote expert successfully. If the issue is understood and interpreted correctly by the remote expert, the lack of knowledge from the customer can also cause them to not be able to solve their issue successfully. Therefore, remote support can be a successful tool if the right technologies are used. To create a remote support solution that is prepared for the increase in complexity of the production environment, Industry 4.0 technologies will be used. More information on why Industry 4.0 technologies are necessary to enable remote support and more in-depth research on these technologies can be found in *Chapter 3. Remote support using Industry 4.0 technologies*.

1.4. Research question

Based on the previously described problem definition, a main research question can be set up, which this thesis aims to answer. The main question is: How can new technologies of Industry 4.0 be used to enable remote support for production machines?

This research question immediately raises multiple sub-questions. By answering these sub-questions, the main question can be answered.

The sub-questions are:

1. Which available Industry 4.0 technologies are suitable to enable remote support?
2. What are the prerequisites of industrial companies to enable remote support?
3. How can companies be guided in the decision-making of initiating and integrating remote support?

1.5. Research methodology and structure of the thesis

The content of this thesis that follows can be divided into multiple sections, where each section aims to answer one of the sub-questions. The first sub-question will be answered based on literature research. This literature research will cover the state of the art of remote support and its core technologies. As these technologies are emerging technologies and thus are not fully embedded into society yet, variation in literature on the definitions of each of these topics in literature will occur. Therefore, it is important to start off with a proper understanding of what these terms will mean in the context of this thesis and how they are interpreted. The second sub-question will be answered by providing a list of requirements that need to be met by industrial companies to successfully integrate remote support. This list of requirements is partially based on the literature found and partially by executing a case study at an industrial production company. The theoretical findings, together with the experiences gained during the case study, will be translated into a roadmap, which will be used to answer the third sub-question. This roadmap will be made to demonstrate how industry can move from local to remote support and what steps need to be taken to achieve this. This roadmap can be used as a guideline for industry so that they are able to implement remote support. The case study for this thesis is executed at Tembo Paper. This case study is done to validate the roadmap and to show how the roadmap can be applied. Besides that, the case study at Tembo also provides two use cases for a proof of concept on what remote support could look like in the future. This proof of concept, which can be found in *Chapter 6. Proof of concept*, is used to discover unforeseen difficulties and opportunities and to test the user experience. Lastly, the combination of the literature research, the roadmap and the validation through the case study will lead to the final conclusions, reflection, evaluation, and recommendations of this thesis. The main question will be answered in *Chapter 7. Conclusion*.

1.6. Scope of the assignment

Researching the above-designed research question can be done elaborately. To ensure an adequate and precise answer to the research question, the scope is defined below. To understand the report, it is essential to grasp what is in and out of scope. This is also important for research that might continue in this direction.

The main issue, as mentioned previously, is that the maintenance engineers currently must fly to the customers to inspect and repair production machines, resulting in significant downtime. This is a time-intensive and costly procedure with great environmental impact. Remote support is mentioned as one of the possible solutions that this thesis will focus on. However, there are other directions that could be explored to resolve the same issues.

An obvious solution is removing the need for remote support altogether by reducing the number of breakdowns the machines have. However, modern-day machines are complex, and while maintenance could be reduced by understanding the machine better, there will always be a chance the machine will break down unexpectedly. Another option is to decentralise the OEM so that the experts can be based near the customers. If all customers have supporting staff nearby, the travel time will be reduced. While this method could be executed based on the size of the customer and on the amount of frequent maintenance needed, it is not realistic to have supporting staff near all customers. While these options are worth exploring, this thesis will solely focus on remote support.

To assist industry in the implementation of remote support, a guideline will be made. Besides that, a proof of concept for remote support will be made to find out what the present-day issues are. This proof of concept will also function as a validation for the findings on the guideline for remote support. This thesis will dive into the different technologies that are required to enable remote support and investigate, as well as lay the first foundations for the application of remote support for industry.

Figure 6 shows the Advanced Manufacturing Landscape, an organisational representation of a production environment [7]. This landscape will be used to approach the different technologies that can be used to enable remote support. The data layer consists of all the systems that are in place in the production environment, such as enterprise resource planning and machine data. The data is usually available for one perspective or process [7]. The middleware is in place to regulate the exchange of data provided by the data layer. The middleware should allow a focus on interoperability to make sure employees don't have to update multiple systems with the same data [7]. As remote support should facilitate the user with perspective-dependant decision-making, the focus of this thesis will be on the information and intelligence layer of the Advanced Manufacturing Landscape. It is therefore assumed that the required data and middleware are already in place to enable remote support.

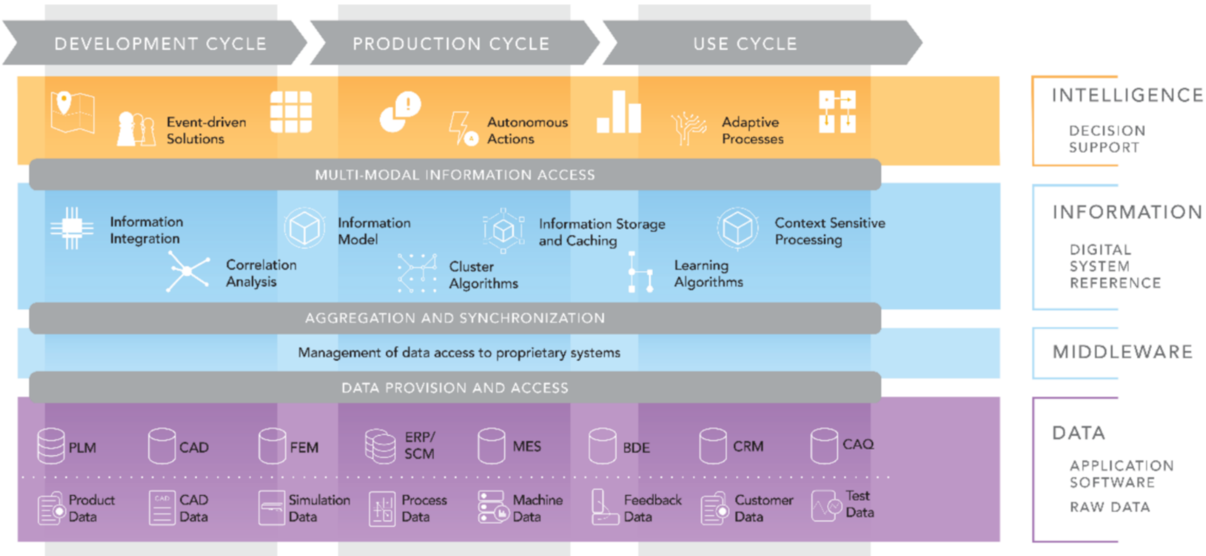

Figure 6: Advanced Manufacturing Landscape, adapted from [8]

2. Analysis

This chapter examines how remote support can be facilitated in industry. First, the case study at an OEM company will be described. Subsequently, a stakeholder analysis takes place, which looks at for whom remote support could be relevant. In addition, the similarities and differences between stakeholders and Tembo are examined in order to provide better advice on the industrial facilitation of remote support.
The case study will be carried out at Tembo. The case study will go into the technological difficulties as well as the user experience of remote support. More information about the execution of the case study can be found in *Chapter 6. Proof of concept.*

2.1. Company analysis

By analysing Tembo and its company characteristics, an idea is created on the relevancy and application of remote support for industrial companies similar to Tembo. The analysis can also create insight for companies with different characteristics on their implementation of remote support.

Tembo Paper is part of the Tembo Group, a global company that produces paper straws as well as the machines that produce these paper straws. Tembo Paper is starting to implement a performance-based business model. With this business model, they are paid based on the output of the machine instead of receiving just one payment per machine sold. This creates an incentive for Tembo Paper to optimise its use of the available services in-house. If Tembo Paper understands the machines at the customer sites, they can prevent downtime by installing the correct components for specific environments. Besides that, Tembo Paper can also lower downtime by monitoring when components need to be replaced before a machine breaks down.

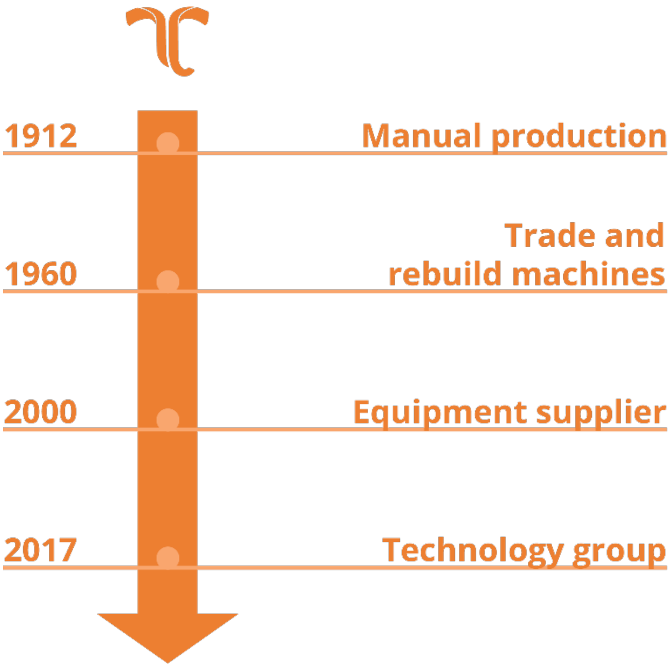

Figure 7: Four generations of Tembo

Tembo Group is a family company with the head office located in Kampen, the Netherlands. The company started as a small cigar factory back in 1912. Today, over a hundred years and four generations later, Tembo group has developed into a technology group (Figure 7). The product portfolio expanded to also include paper straws and detergents. Tembo Group consists of 18 companies, including OEMs, R&D, service, engineering, and product development companies. The biggest OEM is located in Poland, and the services are provided to clients all around the world.

Currently, around 1200 people are working at Tembo Group in ten different countries. Their focus has shifted towards sustainability, which became evident with the founding of Tembo Paper and Tembo Paper Straws. They aim, partially by becoming a digital factory, to create sustainable products by understanding their machines better than their competitors. A digital factory is defined as a production environment where all physical and digital parts share information across all production stages, resulting in real-time operational data and increased efficiency [9, 10].

For the sake of simplicity and adaptability, for other companies within the production industry to adopt the findings of this thesis, the various companies from Tembo group will be assessed as one.

2.2. Stakeholder analysis

Introducing remote support as a service tool involves multiple stakeholders. This stakeholder analysis mentions the involved stakeholders and their interest in introducing remote support.

The lifecycle of remote support can be divided into two parts: the development of a remote support tool and the use phase of remote support. The stakeholders that are involved in the development, as well as the use phase of remote support, are mapped in Figure 8.

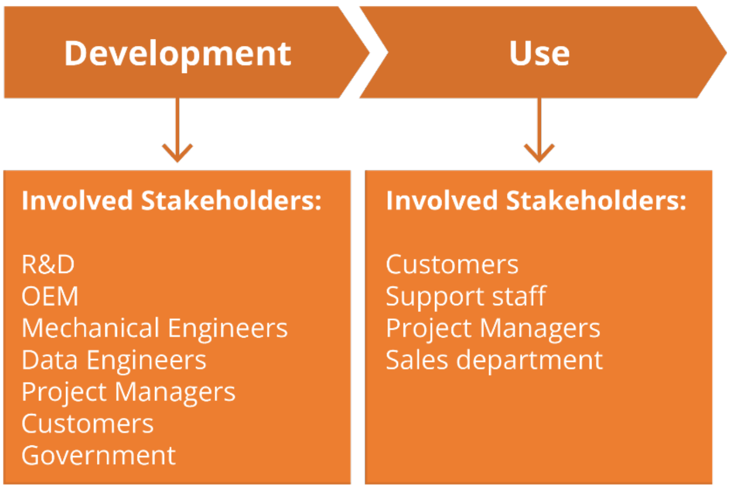

Figure 8: Involved stakeholders during development and use of remote support

During the development stage, the requirements for remote support are set up together with the customers. The R&D and OEM of the machine are directly involved, as they have the best knowledge of the machines and therefore have relevant input for a remote support tool. As mentioned before, remote support will require technologies. As it is assumed these technologies require data of some sort, the input of the data engineers is valuable. The customers need to be closely involved in the development stage, as they need to be convinced to acquire the hardware needed for remote support. Lastly, the laws, e.g., privacy or safety laws introduced by the government, need to be correctly adopted.

The use phase knows two main stakeholders: the customers and the support staff. They are the main stakeholders as they will be the two main users on either side of the remote support. The sales department and project managers are responsible for introducing remote support to (new) customers. The project managers keep close contact with the customers to make sure remote support works according to the expectations of the customers.

2.3. Company characteristics

The more other industrial companies share the same characteristics, the more relevant the results of the use case will be. The first characteristic that is important for the implementation of remote support is that the company is the OEM of the production machines. These machines can be complex, and thus the remote support solution presented in this thesis will allow for this complexity. It is important to understand the machines that are sold and to possess the ability to directly influence change in the machines. Besides that, the OEM must (aspire to) be a digital factory. With digitalisation tools that are available, companies can find and understand the bottlenecks of a production environment. The use case will be executed at Tembo, which is a large company. While the size of the business is irrelevant to the success of the implementation of remote support, the resources required to transform a company into a digital factory are more available amongst larger companies.

Remote support will be a less viable solution to companies that do not have the knowledge of the machines in-house, as they are not able to transfer information and knowledge of the machines remotely to their customers.

2.4. The tipping point for remote support

Remote support is currently still in its infancy. Its main use in industry is found in the IT department, where IT staff can remotely help with computer-related problems, both internally and externally.

While IT-related problems are easily solved, remote support for production machines has not yet been adopted on a large scale. The main cause for this is its technical limitations [11]. However, as technology has advanced, some of these technical limitations have been overcome [12]. Therefore, the next chapter will dive into remote support, its state of the art, and the technologies required to make it a success in industrial applications.

3. Remote support using Industry 4.0 technologies

In this thesis, remote support will be explored to assist service engineers in resolving machine repairs without travelling to the machine. As remote support has been defined in *Chapter 1.3. Remote support*, it is essential to look at the current state of the art. This is done to find expected difficulties and to explore what technologies are currently used to enable remote support. The sub-question "Which Industry 4.0 technologies are available and most suitable to enable remote support?" will be answered in this chapter.

3.1. State of the art of remote support

To see where remote support is headed, it is essential to first analyse where remote support stands currently. Previously, before the introduction of the technologies that are available today, remote support was often described as a tool to send over machine data digitally [5, 13, 14]. However, with the growing complexity of production machines, only sending over data is no longer sufficient [15]. While small software tweaks can be solved remotely by changing parameters, most of the machine's problems are more complex, often hardware related, and require decision-making support from the remote support tool.
More recently, new technologies have been developed that might be enablers for remote support for complex machines. For example, the development of Extended Reality enabling components such as cameras, tracking algorithms and visualisation technologies has changed the possibilities for remote support [12]. Multiple remote support tools have already been created with some of these new technologies [11, 12, 16-18].

The main cause of technological incidents is human errors [19]. The design of remote support needs to be in such a way that technology itself will also eliminate the chance of human errors as much as possible. To deal with the complexity of the machines, remote supporting staff needs tools to transfer their knowledge to the on-site worker successfully. Successful information transfer is especially important as there often is a language barrier between the supporting staff and the on-site workers. The technologies that are used for remote support should therefore assist in visually transferring the knowledge of the remote supporting staff within the context of the problem to the on-site worker. At the same time, it is important that the tools used to facilitate remote support can be incorporated within existing industry structures to lower the threshold for industry to introduce remote support.

Leading industrial companies aim to use different modern technologies to understand their machines from a digital point of view and use the data in context for decision-making. These technologies can be classified as Industry 4.0 technologies.
With the increased complexity of modern-day production machines, problem identification solely via telecommunication is no longer sufficient. To tackle this issue, remote support needs to be integrated with core technologies of Industry 4.0 to be successfully used as a replacement for local support.

3.2. Industry 4.0

As mentioned, Industry 4.0 and its technologies will be used in this thesis to enable remote support and enhance its potential. This chapter will describe the origin of Industry 4.0 and how Industry 4.0 translates to manufacturing, both in the present day as well as in the future. The technologies of Industry 4.0 are explained based on four technology groups. Each technology group has a different function and, therefore, different added value.

3.2.1. Context of Industry 4.0

Industry 4.0 indicates the fourth industrial revolution, following the first industrial revolution (18th century), the second industrial revolution or Technological Revolution (late 19th century) and the third industrial revolution or Digital Revolution (latter half of the 20th century), as can be seen in Figure 9. While the first two industrial revolutions involved physical production, the third revolution created a shift to digital automation by means of electronics and computers.

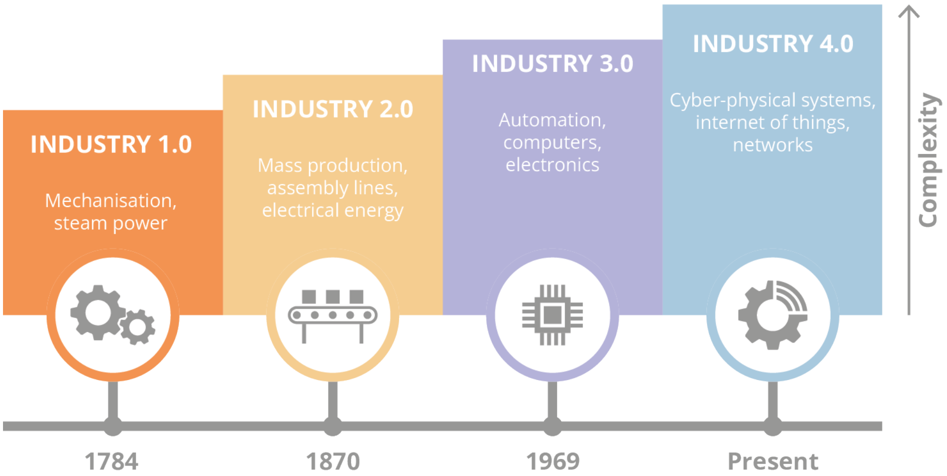

Figure 9: Overview of the four industrial revolutions, adapted from [20]

The shift to Industry 4.0 started in 2011 [20]. Industry 4.0 covers cyber-physical systems and is often connected to terms such as smart industries, smart automation, and interconnectivity. Some of these new technologies are Artificial Intelligence, Advanced Robotics, Digital Twinning and Extended Reality. Industry 4.0 is not just an overarching term that covers these technologies but rather covers the connection and interaction between these technologies [21]. By successfully combining multiple technologies, the boundary between the real and the digital world is partially removed and is perceived as one. As production environments are becoming too complex [15], a mature digital-physical environment can restore overview and avoid human errors as they allow for proper integration of the different pieces of intelligence installed in the production area [22]. The technologies of Industry 4.0 can help to understand the production environment and assist in making the correct decisions, even with today's complexity of these environments.

Even though industrial production companies are still in the process of adopting Industry 4.0 technologies, an idea for Industry 5.0 already exists (Figure 10). Industry 5.0 is said to build on the foundation of Industry 4.0's cyber-physical systems with an additional cognitive layer. Industry will be more human-centred and more focused on producing for personal needs. However, it is expected that Industry 5.0 will not start to be adopted in industry until Industry 4.0 has matured. Industry 5.0 will not be the focus of this assignment, as it is more relevant for digital factories to first focus on properly adapting Industry 4.0 technologies. Still, it is important to keep the trajectory of the industrial revolutions in sight during current developments.

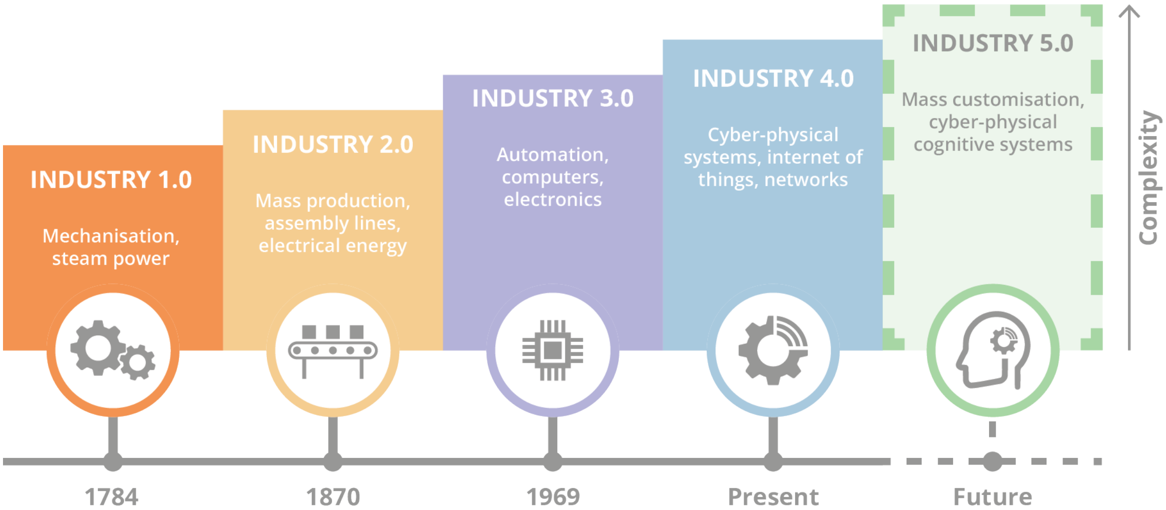

Figure 10: Overview of the five industrial revolutions, adapted from [20] and [23]

3.2.2. Choosing the technologies for remote support

The core idea of Industry 4.0 is creating a cyber-physical system where the digital and real world is interconnected. To understand which Industry 4.0 technologies are available and most suitable to enable remote support, four foundation technology groups are described that categorise the industry 4.0 technologies, as can be seen in Figure 11 [24]. Categorising the technologies helps to focus on what the added value of the technologies is. This helps determine how each technology group can enable remote support.

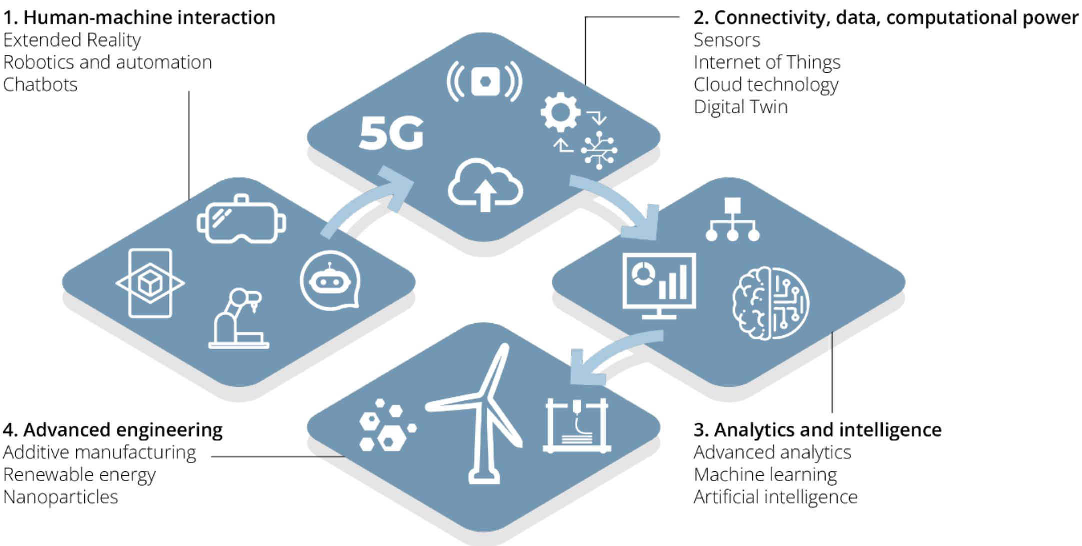

Figure 11: Four foundational technology groups of Industry 4.0, adapted from [24]

The first foundational technology group is human-machine interaction. Human-machine interaction covers the technologies used by humans to interact with machines. The data, information and intelligence form the backbone of this interface. The second group focuses on how different assets can communicate with each other and is called connectivity, data and computational power. This technology group covers not only the raw data but also the communication and processing of that data.
Analytics and intelligence, from the third technology group, are used to understand the data coming from industrial machines, which are getting more complex by the day. Technologies such as machine learning can be used to let a machine recover itself or give suggestions on possible problem solutions based on past events. Lastly, advanced engineering allows for different ways to produce energy and products, which can be more environmentally sustainable, cheaper or faster. The core idea of each technology group, as shown in Table 1, helps to define which Industry 4.0 technologies belong in which technology group. This includes technologies which are not listed in Figure 11.

Human-machine interaction	Interaction and communication between human users and a dynamic technical system through a human-machine interface [25].
Connectivity, data, computational power	Connection and communication between systems, the assistance of calculation through cloud-based solutions.
Analytics and intelligence	Creating actions and insights based on real-time and (predictive) simulated data [26].
Advanced engineering	Using 10 R-based approaches (refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle and recover) for better and more sustainable production [27].

Table 1: Technology group definitions

Each of these four technology groups have different functionality in terms of remote support. Human-machine interaction needs to be in place to allow the user to interact with the machine. An interface that takes care of this interaction can also be used to display virtual data in a three-dimensional (3D) space instead of on the traditional two-dimensional displays. Interfaces for remote support often make use of Extended Reality devices, as they are ideal for displaying information in the 3D space.
Connectivity, data & computational power is essential for remote support, as remote support does not function when the remote expert is not connected to the on-site worker. By using cloud-based solutions, the computational power of the hardware used for remote support can be reduced. However, secure data solutions are necessary to ensure that the information from the customer cannot be intercepted.
Analytics and intelligence can be useful for remote support, but only once a basic application for remote support is already in place. If this is the case, technologies such as machine learning and artificial intelligence can help the on-site worker in decision-making for problems that have happened previously. It can also help in the decision-making of

new problems based on a combination of information from previous scenarios. Advanced engineering is the least connected to remote support of the technology groups. Additive manufacturing could be used for printing temporary spare parts if there are no spare parts available to the on-site worker. The other advanced engineering technologies have no added value for remote support.

To approach the different technology groups in a structured way, the reference architecture model for Industry 4.0 (RAMI4.0) can be used [28]. The RAMI4.0 (Figure 12) is a 3D framework: the process architecture is placed on the vertical axis, the product life cycle on the left-side horizontal axis and the factory hierarchy and responsibilities are placed on the right-side horizontal axis. By aligning the technology groups with the process architecture, remote support technologies can be approached from the bottom to the top to ensure good integration with the production environment.

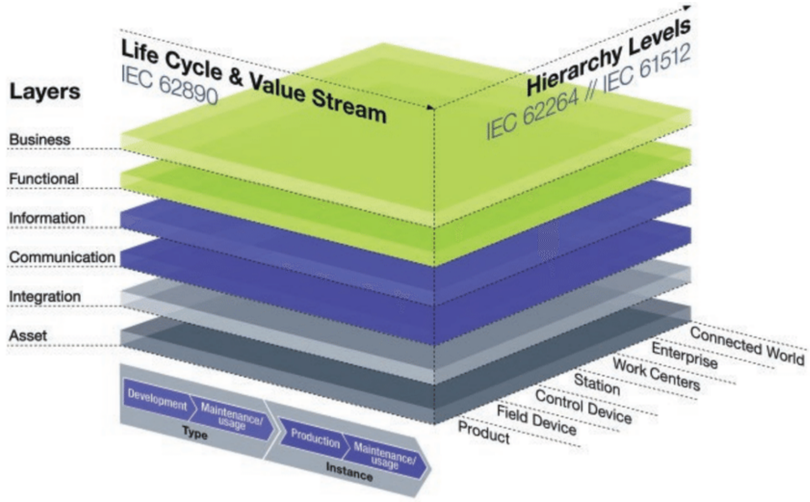

Figure 12: Reference Architecture Model Industry 4.0 (RAMI4.0) [28]

For most industrial companies, not all technologies can be implemented at the same time in the production environment. While the strength of Industry 4.0 lies in connecting these technologies, there will always be priority on which technologies to implement first. The technology groups can be placed in order based on the process architecture of the RAMI4.0 to define the priority for remote support. Figure 13 shows the different architectural layers of RAMI4.0, a description of the layers and which technology groups align with that description. The technology groups have been appointed to the layers that match in their functionality.

Layer	Description	Technology group(s)	
Business	Organisation and business processes		
Functional	Functions of the asset	Advanced Engineering	
Information	Necessary data placed in context	Analytics & intelligence	Connectivity, data & computational power
Communication	Access to information	Connectivity, data & computational power	
Integration	Transition from real to digital world	Human-machine interaction	
Asset	Physical things in the real world	Production machines	

Figure 13: Process architecture of RAMI4.0, adapted from [29]

A production environment is different for each OEM. As the environment forms the basis for what is expected of remote support, it is best to approach the architecture, as shown in Figure 13, from the bottom layer upwards. To interact with the digital side of the physical asset, human-machine interaction is required. However, there must be digital information available to enable user interaction. For this, the connectivity, data, and computational power are in place. The exact information that is being communicated will be the result of two technology groups: analytics and intelligence and connectivity, data and computational power. The technology group of advanced engineering can be used for the functional layer of the asset. However, in the case of remote support, it was decided to only focus on the asset, integration, communication and information layers. The advanced engineering technology group is therefore considered outside of the scope of this thesis. In short, the remote support technologies will be approached based on the technology groups in the following order: human-machine interaction, connectivity, data and computational power, analytics and intelligence, as is visualised in Figure 14.

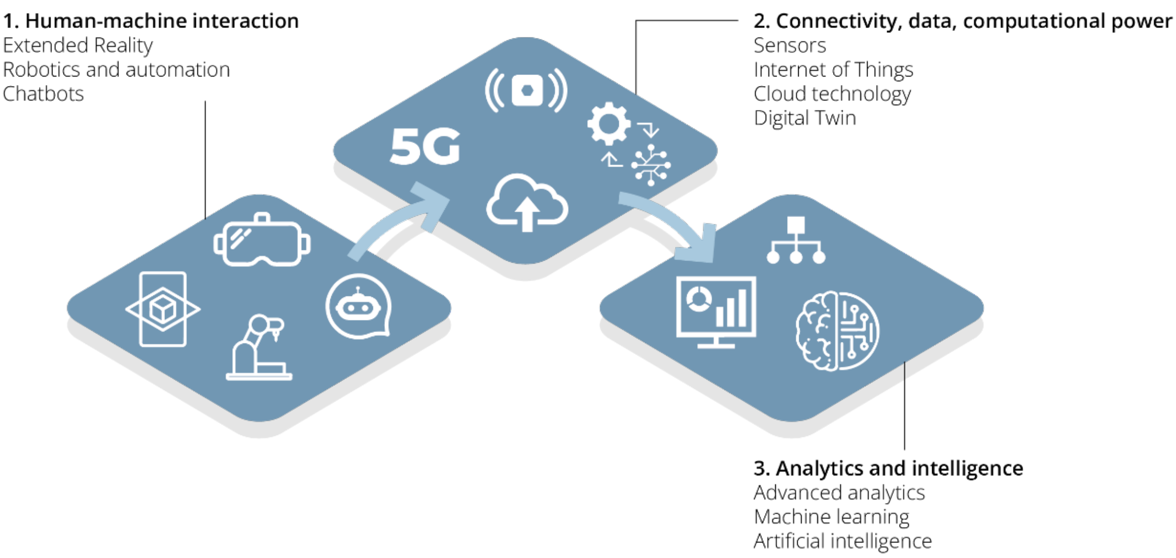

Figure 14: Three relevant technology groups for remote support, adapted from [24]

Based on Figure 14, four technologies that are part of Industry 4.0 that could help enable remote support were selected from the three technology groups. Firstly, it was assumed that Extended Reality, in whatever shape or form, is required for the user to interface with the real and digital world. From the connectivity, data and computational power technology group, Digital Twinning was chosen to form the digital backbone for remote support. It was decided that using the Internet of Things and Cloud technology for external computational power, while it is relevant for remote support, is out of the scope of this assignment. Instead, two different topics were chosen to guide industry in developing remote support. These two topics are human-machine interface, which will focus on connecting extended reality and digital twinning technologies, and Product Lifecycle Management, which will focus on data acquisition for remote support. The next sub-chapters will go into detail on these four topics, which are visualised in Figure 15.

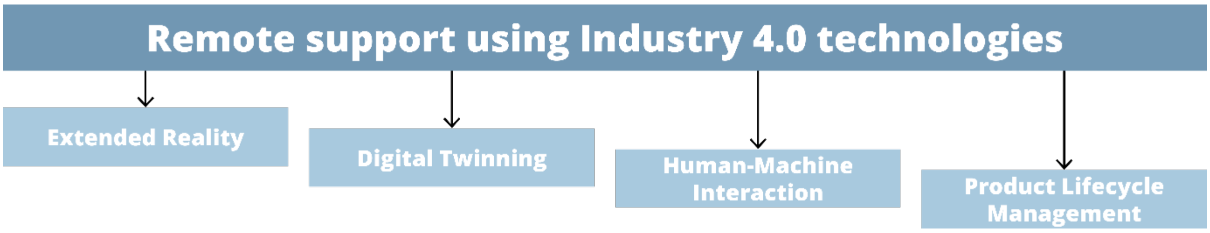

Figure 15: The four chosen technologies for remote support

3.3. Extended Reality

In remote support, Extended Reality (XR) functions as the interface for the user between the physical and digital worlds. In this chapter, the used terminology will be defined, and the industrial applications for XR will be discussed. The bottlenecks of XR, but also the technological advancements in the field of XR will be assessed to define its benefits and drawbacks.

3.3.1. Terminology

XR refers to the combination of real and virtual environments [16], which are the opposite ends of the virtuality continuum [30]. XR is the catch-all term used to describe anything within the reality-virtuality continuum, as shown in Figure 16. In practice, the most found XR technologies consist of Virtual Reality (VR), Augmented Reality (AR) and Mixed Reality (MR). XR technologies allow users to enrich the real environment with virtual objects and use the potential of the 3D space. It is easy to get confused with the terminology and its uses as this varies widely in literature.

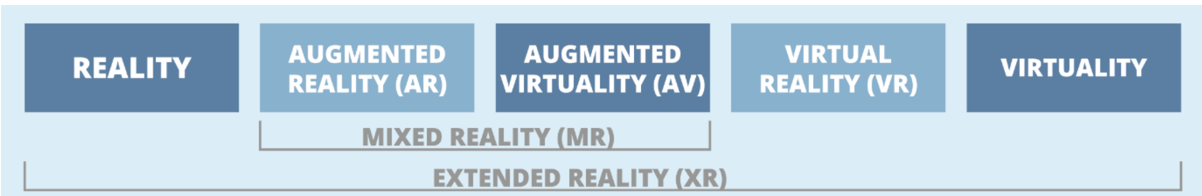

Figure 16: Reality-Virtuality continuum [30]

VR can put the user in a nearly complete virtual environment. When the user is equipped with a VR headset, the lenses show digital images, and the real-world position and rotation are used to align the virtual position and rotation. This way, any movement in the real world is identical to the virtual world. It is, therefore, possible to simulate a production environment without the need for the user to be physically in that environment. This can be particularly useful for maintenance training, as 3D models of the machines that require maintenance are already available to be used in these simulations, and the rest of the environment can be simulated as well.
The benefit of using VR is that, without manufacturing the machine, the user can create a proper perception of the machine and is able to investigate and interact with the machine in an immersive way. If the user has access to a VR headset, their physical location is almost irrelevant, as VR only requires little space for the user to move around physically. If the training is interactive, a digital connection with the trainer needs to be established.

AR allows the user to place virtual objects into the real world. The most common device for AR applications is still the mobile phone. The virtual object that is placed onto the real world is only visible through the screen of the phone. As with VR, the real-world position and rotation are used to align the virtual assets. While mobile phones are the most popular device for AR experiences, it is still very limiting. All interactions with the virtual objects can only be done through the touch screen of the phone. In recent years, many big technology companies have been investing in developing their own AR headset. Through an AR headset, the user can see and interact with virtual objects by grabbing or pinching them. In contrast to the mobile phone, this interaction gives a more immersive feeling as the user does not have to hold the display in their hands.

Augmented Virtuality (AV) can be seen as the reverse of AR. In an AV environment, real objects, e.g., the hands of the user, are placed into a virtual world. AV does not have a substantial benefit over AR or VR in industry yet. Therefore, the term is not well known and is rarely used.

As MR is the combination of AR and AV, and AV is rarely used, many understandably see MR and AR as the same term [31]. Since having two similar terms to describe the same only creates more confusion instead of less, this thesis proposes a distinguishment between MR and AR based on the interaction the user has with the virtual augmentation. If the interaction with the virtual objects is done indirectly, e.g., a touch screen, it is referred to as AR. Once the user can directly influence the objects, e.g., by reaching out, grabbing them, and placing them elsewhere, one can speak of MR. The benefits of XR applications are more visible when the user can interact with them more directly and intuitively.

Instead of adopting the outdated definition of MR, an alternative definition based on a Venn diagram will be used [32]. This new definition is required because of the new applications of MR. While this was not yet relevant before, MR now includes environmental awareness, human responses and inputs, location and positioning and spatial sounds. In this new definition, shown in Figure 17, MR is the overlap between humans, computers, and the environment.

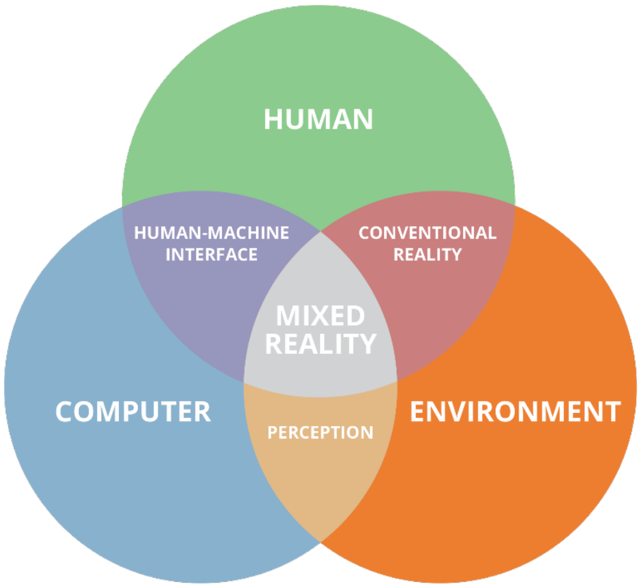

Figure 17: Mixed Reality Venn diagram, adapted from [32]

The environmental input, contrary to traditional human-machine interfaces, is essential for the user to blend their experiences between the physical and digital world [32]. In a current production environment, most overlaps are in place. The employees are able to interact with computers through a human-machine interface, they interact with their environment, and the environment is perceived by the computer through sensors and human input. However, the strength of MR lies in combining them all.

3.3.2. Extended Reality for remote support

Within industry, XR has the potential to enhance current workflows, but the added value of each XR technology differs and has different benefits and drawbacks. The commercial availability of XR devices has raised their use in the manufacturing industry [16]. Because of the increased market share of XR devices, the price has dropped over the past years, lowering the required financial investment and thus making it more appealing for companies to adopt these technologies.

A recent trend in XR devices is the standalone capabilities. For example, while VR headsets used to require a powerful computer to render the virtual world, the calculations can now be done all with the VR headset itself. This was made possible by increasing the hardware specifications of the devices and by reducing the complexity of the applications, which in turn reduces the required computational power. Software developments, such as optimisations in asset calculations, also decrease the hardware specifications. Most XR applications nowadays no longer need powerful computers but can be run from smartphones or similar devices.

In itself, XR does not provide the ability for employees to interact with a production environment [33]. In the case of remote support, the context of the production environment is the basis of the interaction. Visual assets can be provided to the 3D space and are placed within this context. By creating visual assets, common remote support bottlenecks, such as language barriers, can be avoided. To avoid these bottlenecks, software is required that recognises the 3D space and can place the digital assets into the real world. While the currently available hardware is already equipped with multiple cameras to capture the production environment, it only recognizes the distance to the surrounding objects. Based on this, a 3D mesh is made on which the digital content can be placed. However, recognising the correct objects is still a challenge.

3.4. Digital Twinning

A Digital Twin is a key component for the digital transformation of an industrial company. Where XR is the tangible layer that functions as the interface, Digital Twins form the backbone of remote support. Since there is not one true definition of what a Digital Twin exactly is, the first part of this chapter will go over the definitions used in this thesis and in what context the Digital Twin can be used.

At its core, a Digital Twin can be defined as a real-time copy of any physical asset together with all its information, models, methods, tools and techniques to represent the current states of an instantiated system coherently and consistently [34]. The Digital Twin is a digital informational construct and can be seen as an entity on its own but embedded within the physical asset [35].

3.4.1. Digital System Reference

While the term Digital Twin is used often when it is placed in the context of the Digital System Reference (DSR), a useful structure and support for implementation is created [34]. The DSR is an architecture where a Digital Twin, Digital Prototype and Digital Master are used to define different parts of a lifecycle. In the DSR, the Digital Twin functions as the as-is state of the asset. The DSR is shown in Figure 18. As the use case for remote support currently is the most focused on problem identification and problem solving, the as-is state of the model gives the best insight into the possible defects and solutions of one particular asset.

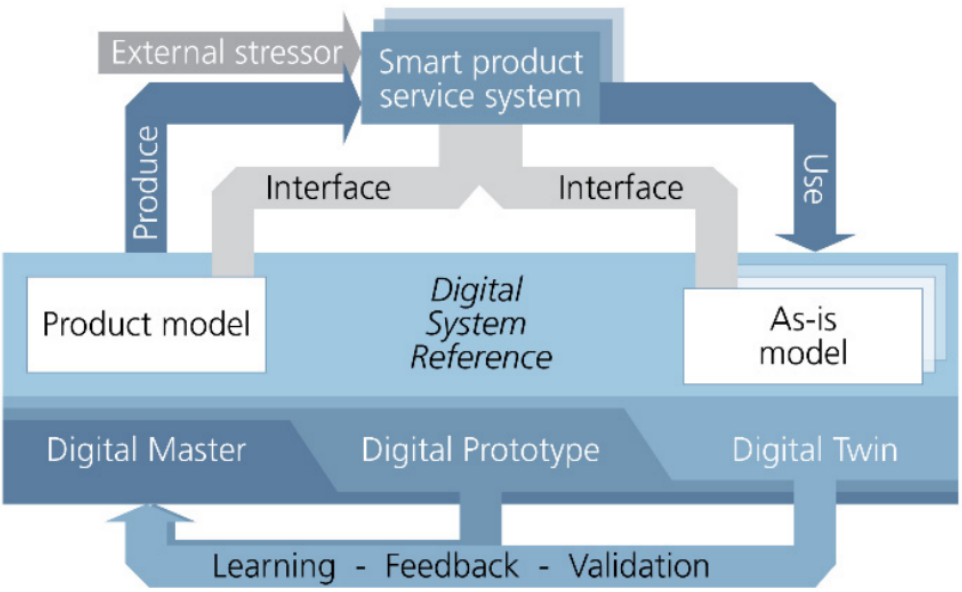

Figure 18: Digital System Reference [34]

The Digital Twin, the digital counterpart of the physical asset, should evolve and update in near real-time to remain relevant. The Digital Prototype is the could-be version of the asset and can be used for what-if scenarios, which helps to predict and anticipate on the future behaviour of the asset [36]. The to-be version, which is the idealised version of the asset, can be improved based on the simulations and assessments from the Digital Prototype [15]. This improved Digital Master then influences the production of new physical assets, and the feedback loop is completed as a new as-is state creates an updated Digital Twin. The Digital Master is useful for remote support as it can be shown to the on-site worker to show what the physical asset should look like. This can assist the on-site worker in finding any anomalies on the machine. For use cases other than remote support, such as providing machine understanding to the operators, the could-be state can be more relevant. The activity of a person or asset using the feedforward and feedback loop between the digital twin, digital prototype and digital master as a whole is referred to as digital twinning [7].
As can be seen in Figure 18, only one product model exists. A product model is the digital to-be version of the asset. Any asset, for example, a production machine, has only one product model, which is the basis for all as-is models. However, many different identical products can be made based on this product model. It can therefore be useful to create a Digital Twin Instance that is linked to one specific instance of the product. This Digital Twin Instance is then able to store information on past measurements, replacement parts and other product-specific information [35].

3.4.2. Digital Twin subcategories

While the idea of a fully automated digital copy of a physical asset has many benefits, it may seem like an impossible task for industry to develop it. To give companies a better grip on how to achieve a true digital twin of their assets, the Digital Twin can be divided into three categories based on the level of automation of the as-is state of the asset [37]. These three categories can help with assessing the maturity of the Digital Twin. When the data flow is fully automated, the as-is state is the most accurate and the least time intensive for employees. An overview of the three subcategories can be seen in Figure 19.

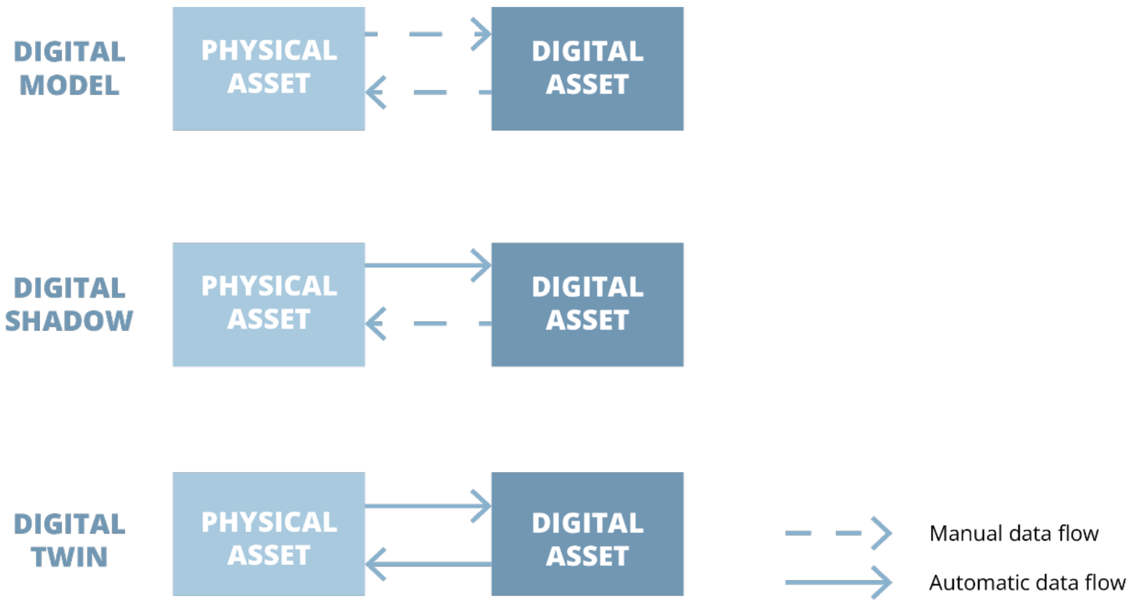

Figure 19: Digital Twin subcategories [37]

Without any automation infrastructure, all data flows from and to the digital asset will have to be exchanged manually. For many companies that are in a transition phase to becoming a digital factory, this is likely the stage they are currently in. In this division, the first stage of the Digital Twin is called the Digital Model. Exchanging all data from and to the digital asset manually is a time-intensive task. When a physical asset has sensors attached, the data from these sensors can be exchanged automatically to the digital asset. However, the data from the Digital Twin still must be manually exchanged to the physical model. This automated one-way exchange of data is called the Digital Shadow.

Once both data flows are automatically exchanged, one can speak of a true Digital Twin. Any change to the physical world will cause an update to the digital world and vice versa. As this does not require any human intervention, this state of the asset is preferred. This subdivision of the Digital Twin is not yet common in literature, and the three subcategories are often still used synonymously [37]. However, its structure is useful for the implementation of digital twinning in industry as each subcategory can be seen as a progress milestone, and therefore these subcategories will be used in this thesis. The DSR and the Digital Twin subcategories can also be combined to create a complete overview. This overview is shown in Figure 20.

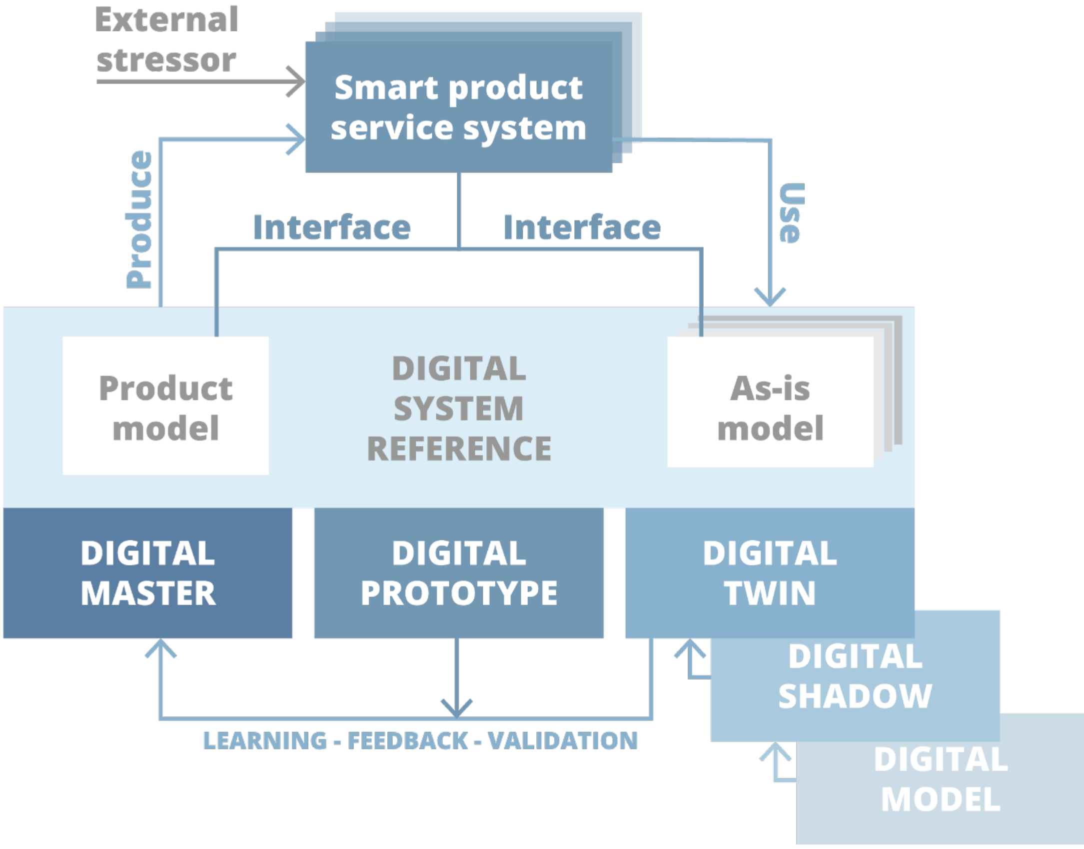

Figure 20: Digital System Reference with Digital Twin subcategories

In this overview, the three subcategories of the Digital Twin are integrated with the DSR. This creates one overview for digital twinning. When this integrated DSR is first implemented, the data flow of the digital twin component is most likely still done manually. In this case, the Digital Model is used. When all data flows of the Digital Twin component are automatic, the Digital Shadow and Digital Model components are no longer relevant and can be disregarded.

3.4.3. Digital twinning for remote support

Regardless of how the data flows in the Digital Twin are set up (manual or automatic), remote support uses the Digital Twin as an information layer. The DSR allows for perspective-dependent decision-making for remote support [7]. But what representation of digital information is required for remote support for it to function as intended?

A Digital Twin should be made only as accurate as is required for its use, not as accurate as is possible [38]. In chapter 3.3, it was assumed that remote support will make use of XR devices as the interface between the user and the digital information. As the computational power for XR devices is often lacking, critical thinking is required to decide what information should be displayed at what time. For large companies, the list of objects that will have a digital twin instance is long. Where a machine can have thousands of individual parts, and the sensors of these machines send data to these instances every few seconds, different techniques can be used to optimise the data flow. For remote support, it is assumed that the software that is used will use object recognition. This way, the digital information can be mapped in 3D space. Just as with the data flows, different optimisation techniques can be used to optimise the recognition of the physical environment. For the accuracy of recognition of the physical assets, only the location data of the asset that the different perspectives require is needed. For remote support, this means that merely the information of which physical assets are near is required to define which instances of the Digital Twin are required. For any remote support application, where a 3D model can be projected on top of the physical object, visible inaccuracies can lead to misinterpretation.

Location-based

One solution to these inaccuracies would be to combine the information Digital Twin instance with the physical location of the asset. For example, when a remote expert wants to identify a machine problem, only the digital data of that specific machine is relevant. By using the location of the XR device of the on-site worker, it can be derived what data set is required to identify the issue.

Octree

Another method to define the relevant digital information is by using the octree principle, as shown in Figure 21 [38]. This tree data structure is used to divide a 3D space into eight segments. For each data point, it can be arranged in such a way that it is part of one of eight segments. The other seven segments can therefore be disregarded. The one segment that contained the one data point can then be divided again into eight segments to find where it is located. The amount of layers of the octree defines the computational power required and the level of detail of an asset.

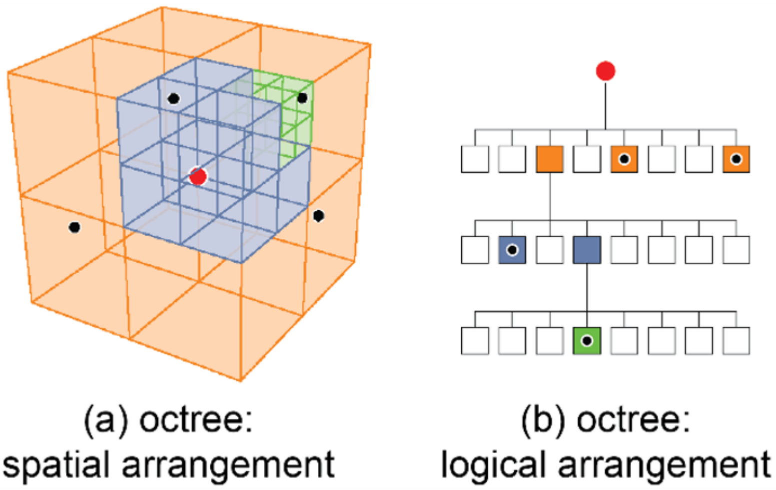

Figure 21: Octree principle [38]

This approach is especially useful for object recognition, as the level of detail can be set depending on the required perspective. For example, to guide an on-site worker to a correct module of a machine, the lowest level of detail can be used. On the other hand, when a small screw inside the machine needs to be replaced, the level of detail needs to be higher. The lowest level of detail (one reference point) can also easily be combined with

the location-based method described previously.
When implementing an octree-based system, the level of detail could also be defined on how often a certain component is looked at or reviewed. In this case, parts such as nuts and screws need a low level of detail, while large gears might need a high level of detail.

3.5. Human-Machine Interaction

People have been interfacing with machines since the first industrial revolution. With the introduction of electrical equipment, it became possible to use buttons and switches to operate the machines. These buttons and switches were grouped together and aligned in a logical and understandable way, and thus the first Human-machine Interaction (HMI) was created.
Nowadays, most HMI no longer consists of physical buttons and switches but digital interfaces on computers, tablets, and phones. The latter two have the benefit of being portable devices. An operator could then control the machine from wherever they were located, if the wireless connection allowed this.

This movement is exaggerated even more with the digital transformation of Industry 4.0. Emerging technologies such as XR provide new ways of interacting with machines. Physical buttons turned into digital buttons during the third industrial revolution (Figure 22), and now these digital buttons are contextualised into the real world instead of on a portable display.

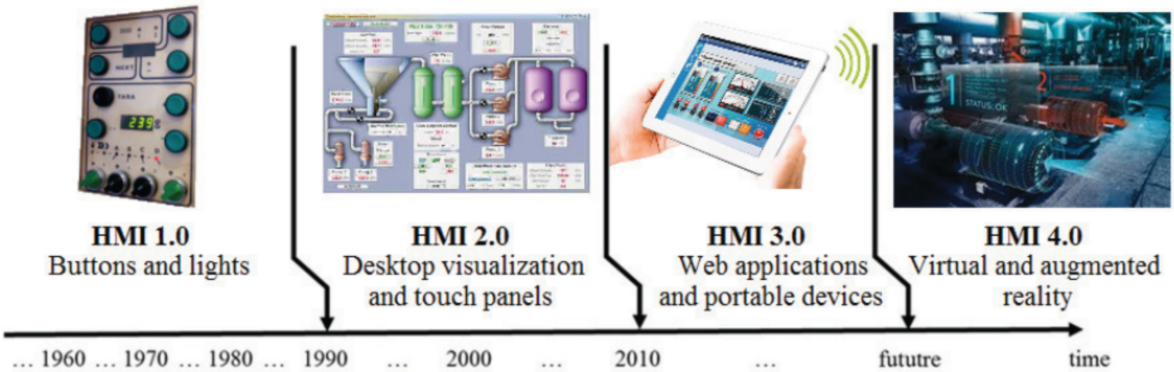

Figure 22: Revolutions of HMI [33]

More importantly, XR interfaces are the first variant of the HMI where the interaction can take place in a 3D context instead of on a 2D interface. 3D interfaces enable new options for interaction and operation of the machines but also limit some 2D interactions users were used to. For example, as the 3D interface on XR devices is no longer physical, there is no longer physical feedback when pressing a button.

If the HMI is properly designed and used, it will positively influence the OEE [39]. As an increase in OEE is one of the motivators to start with remote support in the first place, the correct adoption of HMI implementation is important. Correct implementation of HMI will allow digital decision-making support, with a decrease in potential human errors [39]. As the design of HMI for remote support is different than traditional 2D interfaces, the approach for designing such an HMI is different too.

The HMI design can be approached from three different levels of user activity: physical, cognitive and affective [40]. The physical part covers the different mechanics of interaction, the cognitive level covers in what way the user understands and uses the ways of interaction, and the affective level covers how much the interaction is a pleasant experience for the operator. The latter level is especially important for remote support, as the XR interface will eventually replace the old HMI. If the users dislike the new HMI, they can refrain from using these new technologies. An affective attitude towards the use of the HMI will also increase the effectiveness of its use, especially in an automated and digitalised production environment [39].

The possible physical interactions are partly dictated by the chosen hardware supplier. While it does not matter what mobile phone or tablet is used to run a web-based HMI, the standard gestures and interactions are decided by the hardware manufacturer. For example, the main menu on the HoloLens 2, an XR head-mounted display (HMD) developed by Microsoft, is opened by looking at the wrist and pinching the thumb and index finger. This specific combination of actions is not intuitive and is not found in other similar devices.

3.5.1. Human-Machine Interaction for remote support

As mentioned, one of the drawbacks of 3D HMI is that the physical feedback can be limited. In this case, the physical and cognitive levels of the HMI blend together. The mechanics of interaction only work correctly if the user understands how the interaction should take place. The chosen interactions should be intuitive to the user to keep an optimal workflow. If the user must focus more on what actions they should perform on the HMI, they are less focused on their work and more prone to make errors. Besides error prevention, safety should also be considered in the design of the HMI. During user tests, which are explained in more detail in Chapter 6. Proof of concept, there are two factors that came out as the biggest factor for safety issues: immersion and distraction.

Often, immersion is described as a positive aspect of XR. It allows the user to feel like they are inside the virtual environment. From a safety point of view, however, this is a negative aspect. Especially on a production floor, not noticing or reacting to your surroundings can harm the user or employees around the user. This same effect is caused if the interface of the HMD has too many impulses for the user to process effectively. This can distract the user and can cause harm to the user or surrounding employees.

By designing an HMI that is minimalistic in the information shown to the user, the distraction and immersion are kept to a minimum, which ensures an optimal environment for the user from the perspective of safety. The process of Product Lifecycle Management can be used to make sure the right information is presented to the right person, asset or decision-maker, in the right place, at the right time [7]. This will not only ensure that the users are less likely to make errors, but an understandable presentation of the correct information will also lead to better decision-making and increased productivity [39].

3.6. Product Lifecycle Management

Managing the information throughout the lifecycles of products and services is not a novel concept, but the way it is implemented has changed over time. The first generation of PLM was mostly focused on sharing computer-aided design (CAD) data, since files were often too large to store on computers [41]. This can be seen as PLM 1.0. A decade later, more functionality was required, such as collaboration tools and file security. This is seen as PLM 2.0. PLM 3.0 introduces more focus on managing the requirements, product innovation and supply chain processes [41]. Industry 4.0 demanded a PLM solution where the data and information required could be accessed from anywhere using cloud technology. This chapter describes the PLM technologies within Industry 4.0 and elaborates on the application of PLM for remote support.

It is important to have a proper Product Lifecycle Management (PLM) in place where the right information is available at the right time, to the right employee, and in the right place. A machine operator might want to see which parts of the machine are defective or are almost in need of replacement, while a spare parts manager might want to see which parts have a critically low amount of replacement parts in stock. It is, therefore, important that a production company has a clear view of which employees require what information.

All data and middleware that is used to create a digital foundation to allow for digital twinning are referred to as the digital infrastructure [7]. To use remote support for decision making, this digital infrastructure needs to be in place. Most modern-day production machines are richly equipped with sensors to acquire as much data as possible. However, more data also introduces the risk for companies to be “data rich, insight poor”[42]. Therefore, it is important for companies to define how to structure the information. Currently, many companies in industry are still focusing on collecting the data. On top of that, there still exist issues where the acquired data cannot be communicated to different components, and the middleware is still not designed to function with all available components [7]. It is expected that once the data and middleware layer is in place, context and perspective will enable the information and intelligence layers of the Advanced Manufacturing Landscape (Figure 6, p. 16) for perspective-based decision-making.

3.6.1. Product Lifecycle Management for remote support

For remote support, it is important that only the information that is needed is displayed to avoid distraction. On top of that, minimal interaction makes for fast and accurate decision-making. To show the importance of only displaying the necessary information, two examples are shown in Figure 23 and Figure 24. They make use of the same environmental context, but the digital information that is added is different. The displayed information can also be of different parts of the lifecycle.

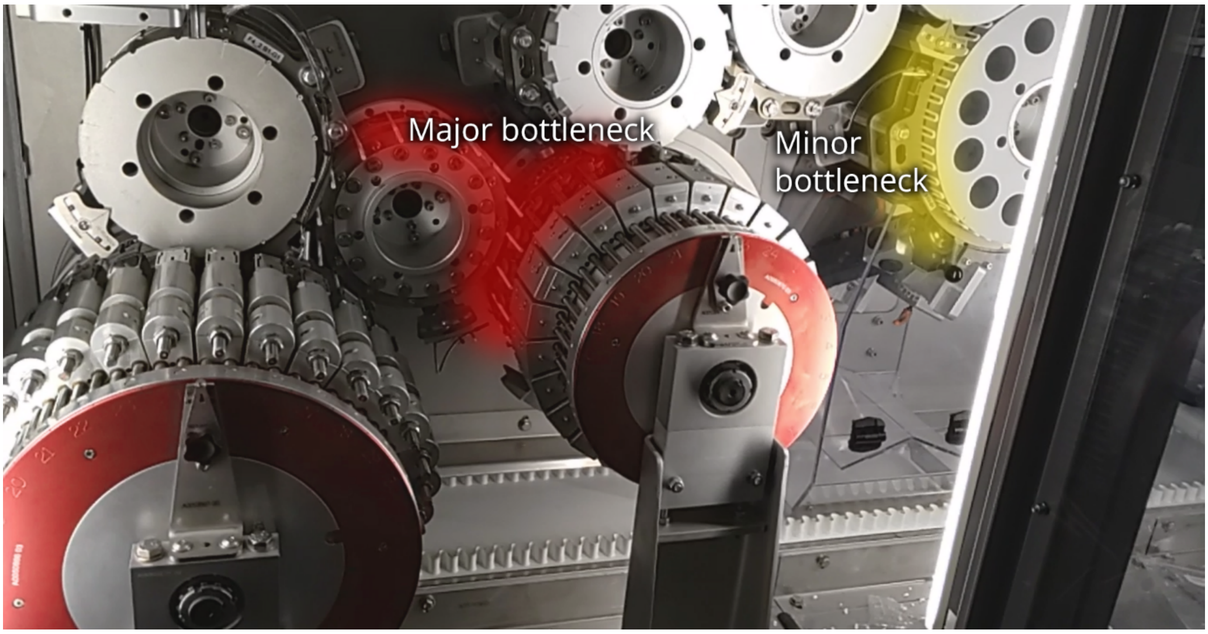

Figure 23: Bottleneck overlay

In the example shown in Figure 23, the areas of the machine that are most responsible for failures are visualised. For a continuous improvement engineer, this can give quick insights in what parts of the machine need attention.

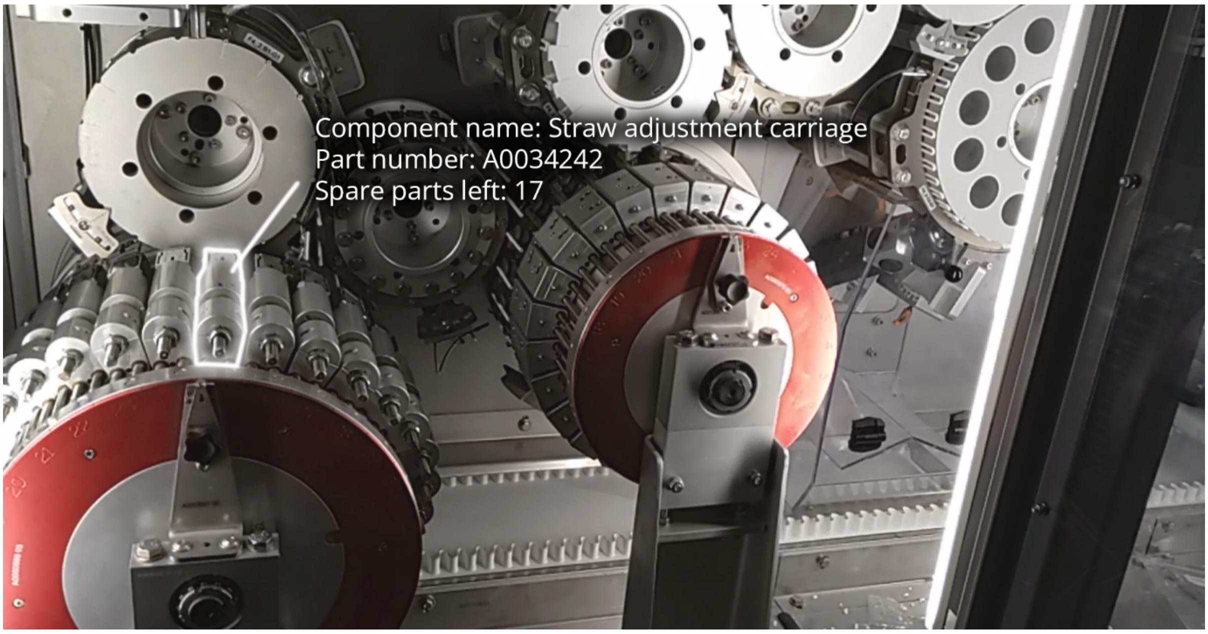

Figure 24: Spare parts overlay

In the example shown in Figure 24, information on a spare part is displayed. In this example, the name of the component, its part number and how many spare parts are left in stock are displayed. For a spare parts manager, this can quickly display the relevant information on whether new parts need to be ordered or not.

The two examples show vastly different information, but both show only the information that is required by the user. Figure 25 shows an overlay where both the bottleneck and spare part information is displayed. As it is unlikely that information on both is needed simultaneously, this only causes unnecessary distraction. A good PLM system needs to be in place to make sure the right information is available to the right person at the right place.

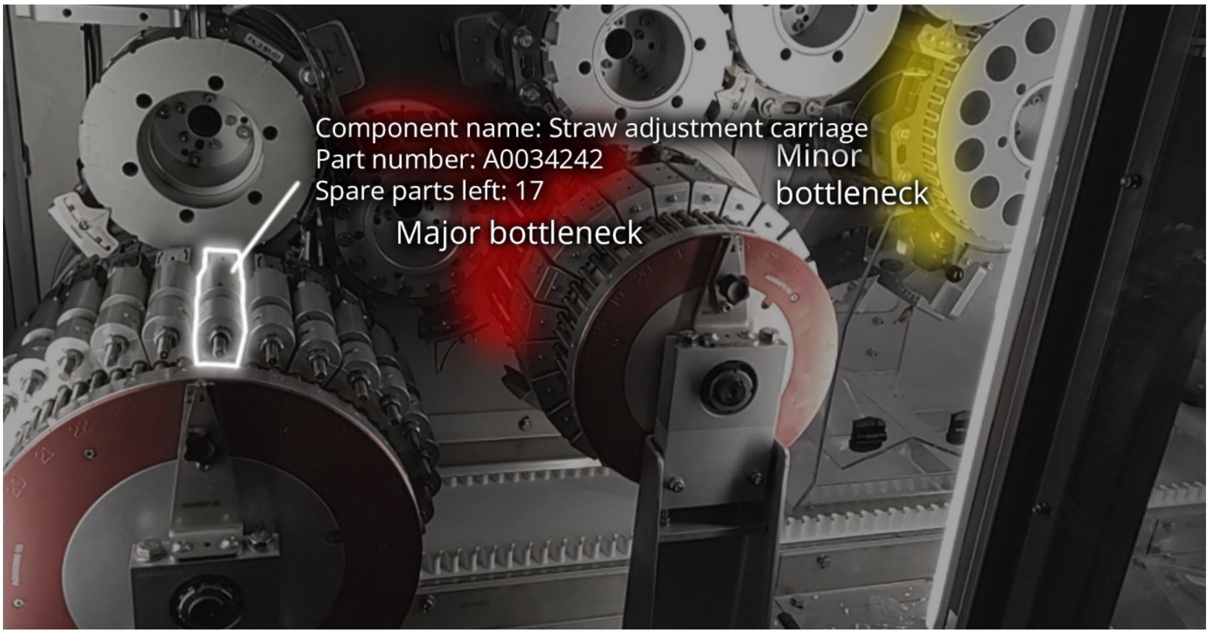

Figure 25: Bottleneck and spare part information

3.7. Conclusion

To answer the sub-question "Which Industry 4.0 technologies are available and most suitable to enable remote support?", literature research was conducted on four Industry 4.0 technology groups, of which four Industry 4.0 technologies were chosen. These topics were Extended Reality, Digital Twinning, Human-Machine Interaction and Product Lifecycle Management. The relation between the different technologies and remote support is shown as an overview in Figure 26.

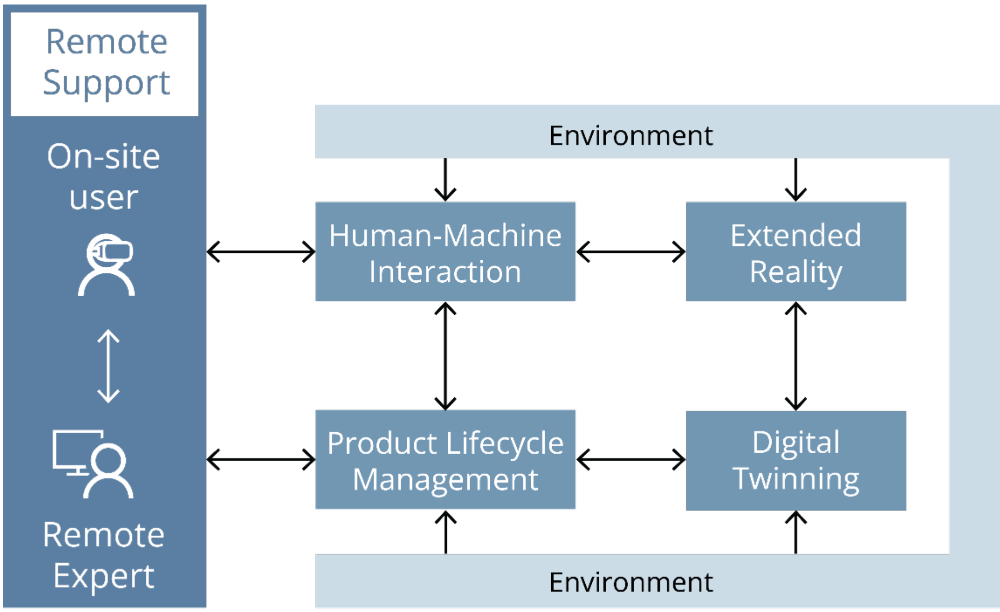

Figure 26: Overview of remote support

XR is used as the human-machine interface and will be at the core of remote support to enable remote supporting staff to transfer information and knowledge to the on-site worker. If the on-site worker uses XR HMDs, they are able to perform maintenance hands-free.
Digital Twinning enriches the on-site worker with digital information. This can be any information that is required for their task, such as, but not limited to, the number of spare parts, critical anomalies, and almost worn-out components.
To ensure that the on-site worker gets the right information at the right time and place, a PLM needs to be in place. Not only the on-site worker but also the remote expert needs access to the necessary digital information for accurate and fast problem-solving.
A PLM system is also important for HMI, as too many unnecessary impulses could distract the on-site worker. This can increase the possibility of human error. HMI can also positively influence the on-site worker. If the way of interaction feels intuitive and pleasant to use, the on-site worker is more eager to use remote support again.

The on-site worker has a physical connection with XR, as they are equipped with an XR device during remote support. Asides from the desired comfort the XR device should bring, the digital connection is more important as it influences the safety and OEE.
The digital content for the XR device is provided by means of Digital Twinning. The current

state information is provided by the Digital Twin Instance, the simulated state by the Digital Prototype and the to-be state by the Digital Master. This way, the on-site worker is able to see what is currently wrong with the machine by looking at the Digital Twin Instance and is able to see what it is supposed to be by the Digital Master. If the on-site worker wants to see what happens when he performs a proposed fix, the Digital Prototype could be used instead of the physical machine.
The necessary data to establish Digital Twinning is provided by the Product Lifecycle Management system. If the data is provided in context and from multiple perspectives, it can be used by the on-site worker for decision-making by incorporating it with the HMI. The OEE is calculated from the data of the PLM system. Changes that are made in the other components that appear in the system contribute to the OEE positively or negatively. Connecting all the components is therefore important to understand how a higher OEE can be achieved.

The environment is often a large unknown in production environments. For production machines, small changes in humidity or temperature can change the quality of the product. While fixes on the machine itself can be accurately logged, information about the environment is often not linked to these fixes. For each of the components, the environment can be an influencer.
For XR, the environment is the physical asset where digital information can be projected onto. XR devices are able to track the environment in real-time. For Digital Twinning, environmental data is needed to accurately describe the digital asset. For HMI, the information needs to be displayed in such a way that the environment does not cause safety issues to the on-site worker, and that the on-site worker is not a safety issue for its environment. The product environment functions as the input for the PLM systems. Modern machines are equipped with different kinds of sensors, e.g., to find defects or track temperatures. Changes in the environment will therefore change the input of the PLM. It is likely, with the advancements of technology, that the production environment will change. This will, in turn, change the requirements of the different components that are in place for remote support.

4. List of requirements

In this chapter, two lists of requirements are set up. First, a list of requirements for the general use of remote support is set up. The categories and the requirements of this list are based on the analysis and the input of the employees of Tembo. The list of requirements for the general use of remote support is divided into functional and technical requirements. Scenario-based thinking is used to define the functional requirements of this first list. Consequently, the list of requirements is divided into multiple categories to create a better overview. These categories were defined during the bi-weekly remote working pilot meetings held with the employees of Tembo. The categories that were chosen as important categories are connectivity, safety, comfort, ease of use and privacy.
Secondly, a list of requirements is set up for a roadmap that helps to integrate remote support in the production environment. This list of requirements is verified at the end of *Chapter 5. Roadmap*, and validated in *Chapter 6. Proof of concept*. This list of requirements solely concerns functional requirements.

4.1. Scenario

To define the functional requirements for remote support, a scenario was set up where a remote expert helps a customer wearing an HMD. It is assumed that an HMD will be used in the remote support solution, as it allows the user to work hands-free. Below is a scenario which is divided into eighteen steps so that it can be referred to easily. The functional requirements list which step of the scenario it is applicable to.

1. An employee of the customer encounters a problem with a machine in the paper straw production line.
2. No employees of the customer recognize this issue or know how to fix the problem.
3. One of the employees gets the HMD and places it on their head.
4. The service department is called with the HMD.
5. One of the remote experts accepts the call.
6. The customer describes the problem as they perceive it. The remote expert can see the view of the customer through the HMD.
7. The remote expert uses the textual description as well as the video footage to determine the problem.
8. The remote expert suggests a solution. The customer did not fully understand the suggestion as the production lines around them were still running and making noise.
9. The remote expert makes a screenshot of the machine's configuration from the manual. They augment it in front of the employee and repeat the suggestion.
10. The customer understands the suggestion based on the explanation and the visual context given by the screenshot they see in front of them.
11. The customer tries different configurations based on the suggestions of the remote expert.
12. The customer starts to lose focus because of a headache caused by the headset attached too tightly.

13. To avoid any misconception about which part they mean, the remote expert adds a visual highlight to this component.
14. The connection is not stable. Therefore, the connection between the remote expert and the customer is temporarily lost. The remote expert is not able to confirm if the customer understands correctly. After a minute, they reconnect automatically.
15. The problem is identified, and a replacement component is ordered.
16. When the replacement part comes in, the customer is assisted by the remote expert with the installation of the replacement part.
17. After installation, a test run is done. The employee compares the machine's output to the graph of the sensor data to see if they are aligned.
18. The machine works properly again, and the call is closed.

Based on this scenario, the analysis, and the input from the employees of Tembo, the following list of requirements for remote support solutions was set up. They are divided into functional requirements and technical requirements.

4.2. Requirements of remote support

Below, the functional and technical requirements of the general use of remote support are listed. The scenario numbers to which the functional requirement applies are listed between brackets.

Connectivity

The connection between the employee and the remote expert can be one of, if not the biggest, bottleneck for remote support.

	Functional requirements	Technical requirements
1	The HMD has audio-visual input (8, 9, 10, 13) (From remote expert to user)	A visual digital overlay on top of the real world
		The input of the microphone of the remote expert is sent to the HMD's speakers
2	The HMD has audio-visual output (6) (From user to remote expert)	The information of the camera(s) of the HMD is transferred to the remote expert
		The input of the microphone of the user is sent to the speakers of the remote expert
3	A connection with a digital asset is in place	The remote expert can access the current state (Digital Twin Instance) as well as the to-be state (Digital Master)
4	Both users (on-site worker & remote expert) have access to the right information, at the right time and place	
5	A sufficient internet connection (14)	Download speed above 10 Mbps
		Upload speed above 2 megabits per second
		Latency below 500 milliseconds

Safety
The safety of the employees should be guaranteed during remote support

	Functional requirements	Technical requirements
1	The HMD is food safe so that it can be used in a food machine production environment (1)	The HMD follows the ISO 22000 food safety standards
2	The HMD is safe to use for the user and surrounding employees	The immersion created by the HMD should not interfere with the awareness of the user of their surroundings.
		The HMI should only show the information necessary
		The HMD warns for possible harmful actions

Comfort
The comfort of the user during remote support is important to stimulate its use and to avoid aversion of the user.

	Functional requirements	Technical requirements
1	The HMD is comfortable to wear (12)	The user must be able to wear the HMD for a minimum of one hour without discomfort
2	The headband of the HMD can be adjusted to fit different head sizes	A small knob is present on the HMD to adjust the strap circumference

Ease of use
As remote support intends to replace a currently functioning way of working, it should be easy for users to switch to remote support.

	Functional requirements	Technical requirements
1	The remote support tool is easy to use (10)	The user must be able to successfully use the application after a training of maximum one hour

Privacy
As remote support uses data from the customer, it is important to make sure this data is secured properly.

	Functional requirements	Technical requirements
1	The connection between the user and the remote expert is secured	The connection follows ISO 27001 standards
2	The connection between the HMD and the cloud data is secure	The connection follows ISO 27001 standards

4.3. Requirements of the roadmap

Meeting all the requirements for general use of remote support is not an easy task. To help companies with the integration of remote support into their production environment, a roadmap is designed. For this roadmap, the following requirements were defined for the creation of the roadmap

1. The roadmap translates a vision to a long-term strategy plan
2. The roadmap defines the scope of the strategy plan
3. The roadmap gives insight in the advancements of enabling technologies
4. The roadmap aids companies by aligning technological advancements with their strategy and vision
5. The roadmap can convert a strategy and vision to an action plan
6. The roadmap must be applicable to any OEM
7. The roadmap allows OEMs to communicate the strategy, vision and action plan with their customers

4.4. Conclusion

The second sub-question was "What are the prerequisites of industrial companies to enable remote support?". With the defined requirements and the analysis done in *Chapter 2. Analysis*, there is enough information to formulate an answer to the second sub-question.

The first prerequisite is that the company is an OEM. OEMs are the most capable of remotely supporting their customers, as they have all the information about the machines. Another prerequisite is that remote support contributes to achieving long-term strategy goals. Using the performance-based business model increases the incentive to enable remote support for OEMs. The employees of the OEM, as well as the customers of the OEMs, should have the incentive to use remote support as a tool instead of conventional methods. For example, if the tool is easier to use, or if remote support takes less time to solve a problem, users are more likely to replace the conventional methods with remote support. On the other hand, industrial companies also need to be willing to invest in the different technologies that are required to enable remote support. The aspiration to be a digital factory help to lower the threshold to invest in new technologies, as a digital factory has the correct data and middleware layers in place.

5. Roadmap

Having answered the first two sub-questions, and having set all the requirements, a roadmap is designed to answer the third sub-question "How can companies be guided in the decision-making of initiating and integrating remote support?". This roadmap is created to assist industry in its efforts to incorporate a new tool, such as remote support, in their current practices. Implementing such a new tool and therefore adjusting the current workflow can be a daunting task. By using this roadmap, a set of actions can be derived to successfully implement remote support. The roadmap itself will contain multiple different components. For the roadmap to be understandable, the individual components will be explained first.

The focus of this thesis is on remote support. However, to create more value to the roadmap, different use cases can be implemented with the use of the roadmap as well. This way, an action plan for other use cases that make use of (different) Industry 4.0 technologies can still be derived from the same roadmap. Remote support is chosen as the use case, as it is deemed to create the largest value in relation to the time required to realise it [43]. Therefore, remote support will be chosen as the use case for the validation of the roadmap, which can be found in *Chapter 6. Proof of concept*. Other examples of use cases in a production environment are machine understanding, VR training, and XR assembly instructions.

The roadmap for this thesis has been developed for the production environment of Tembo. However, any production company of different fields that meets the same company characteristics as described in *2.3. Company characteristics* qualifies to implement the same roadmap. For the design of the roadmap, a four-segment timeline will be used, as shown in Figure 27. This timeline will be used to determine the vision and strategy and to assess and predict technological advancements.

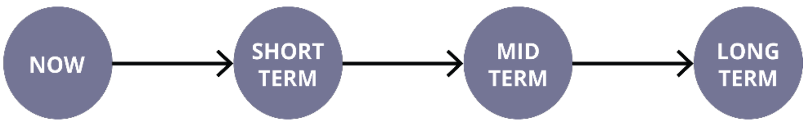

Figure 27: The roadmap implementation timeline, divided into four segments

5.1. Strategy and vision

First, before a production company can start the procedure of integrating new technological tools, it must fit into the long-term strategy plan and vision of that company. Based on the four-segment timeline, as shown in Figure 28, the strategy should be approached backwards. First, the long-term vision is defined. A method called backcasting can be used, where the events and actions that are required to reach this vision are defined based on the long-term vision [44].

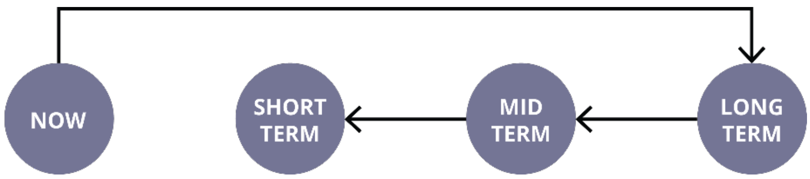

Figure 28: Roadmap definition phase timeline

For use cases such as remote support, backcasting can be a difficult task. There are many new technologies in play that are unknown to the people involved in creating the long-term strategy plan. Besides the unknown territory, bottlenecks that currently limit a use case can create a limited view of the long-term plan. For example, the hardware capabilities of XR devices are not yet mature. While it is expected that these capabilities will advance as time goes on, people can get stuck on the issues that are faced today.

Instead of starting development and realigning and evaluating along the way, it is recommended that companies take the time to develop a long-term strategy. Any limitations, such as the hardware capabilities that are visible in the present, but also short-term and mid-term, should be excluded. The long-term strategy should be developed with a "what-if" mentality, where everything is possible. What added value does it create? What are the use cases where it shows its value?

5.2. Technological advancements

When production companies are looking at a new tool, such as remote support, it is easy to look at the limitations of today. However, expected developments are relevant in each of the technologies described in *Chapter 3. Remote support using Industry 4.0 technologies*. To be ahead of the technological advancements, it is advised to be prepared and set up for these advancements. This way, once commercial solutions present themselves to industry, adopting these technologies will be easier.

Once the different technologies that are required for a use case are defined, an important decision needs to be made. This decision is whether the knowledge and implementation of each of these technologies should be done in-house or should be outsourced. In the case the decision is made to develop technologies in-house, preparation can start early on. If the technology is outsourced, no preparation is required. This sub-chapter will map the technological advancements for each of the four Industry 4.0 technologies discussed in this thesis, as shown in Figure 27. This process is called technology roadmapping, which helps to provide stability in the uncertainty of technological advancements [45].

5.2.1. Extended Reality

The predicted technological advancements for XR are shown in Figure 29. For XR, currently, there is no industry standard. While some companies are exploring their options with HMDs, most companies are not yet applying XR in their production workflows. In the short term, it is expected that more companies will adopt this technology and will mainly use their mobile devices and some XR HMDs to add digital content to the environment. Mobile devices are a good entry point, as most employees are already equipped with one. Mid-term, the XR HMDs will be the main technology enabler, as they allow for a more intuitive way of interaction and allow the user to operate the device hands-free. In the long term, the XR HMDs will be more compact and less obstructive than their predecessors.

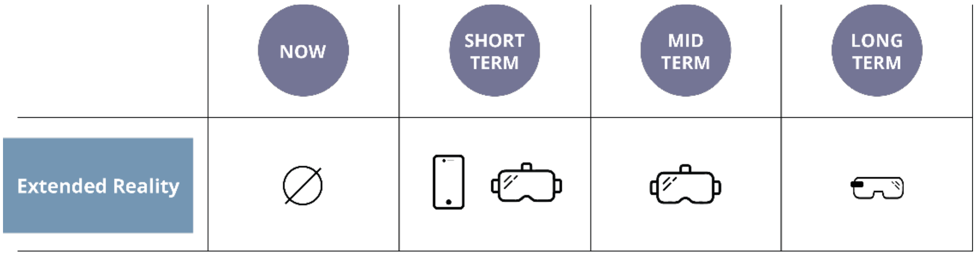

Figure 29: Timeline of the technological advancements of Extended Reality

5.2.2. Digital Twinning

Figure 30 shows the expected advancements of the data flows of Digital Twinning. The theory of these Digital Twin subcategories is previously discussed in *Chapter 3.4. Digital Twinning*. Currently, most data is transferred manually based on who needs what information. In the near future, some of these data flows from the physical asset to the digital asset will be automatic. Mid-term, it is expected that all data flowing from the physical asset to the digital asset will no longer require manual intervention. In the long term, the data flowing from the physical to the digital asset and vice versa will all be automatic.

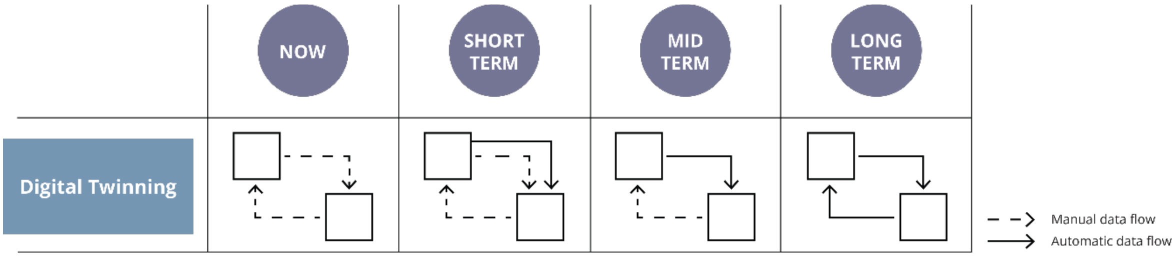

Figure 30: Timeline of the technological advancements of Digital Twinning

5.2.3. Human-Machine Interaction

The technological advancements of Human-Machine Interaction can be seen in Figure 31. The main change over time for this is that the interaction itself between the user and the machine changes from 2D to 3D. Where currently, all HMI is on 2D displays on a screen attached to the machine or on an interface of a computer or tablet, this will change to 3D displays once XR has matured. By changing the interaction to 3D space, the information that is displayed can be mapped to the exact 3D location.

	NOW	SHORT TERM	MID TERM	LONG TERM
Human-Machine Interaction	Only 2D	2D + 3D	2D + 3D	Only 3D

Figure 31: Timeline of the technological advancements of Human-Machine Interaction

5.2.4. Product Lifecycle Management

Figure 32 shows the timeline of the different layers of the Advanced Manufacturing Landscape (Figure 6, p. 16). The four layers are mapped with the four segments of the timeline. As the PLM systems within industry develop, they will enable better decision-making within the given context and from multiple perspectives.

	NOW	SHORT TERM	MID TERM	LONG TERM
Product Lifecycle Management	Data	Middleware	Information	Intelligence

Figure 32: Timeline of the technological advancements of Product Lifecycle Management

5.2.5. Overview of technological advancements

The technological advancements of the four different technologies are displayed in an overview in Figure 33. The technologies are not completely separated. An increase of maturity in one of the technologies can create maturity of another technology. For example, once XR HMDs become the standard in industry, 3D HMI design will mature too.

By closely watching the technological advancements and planning accordingly, companies can step in at the desired maturity of the technology.

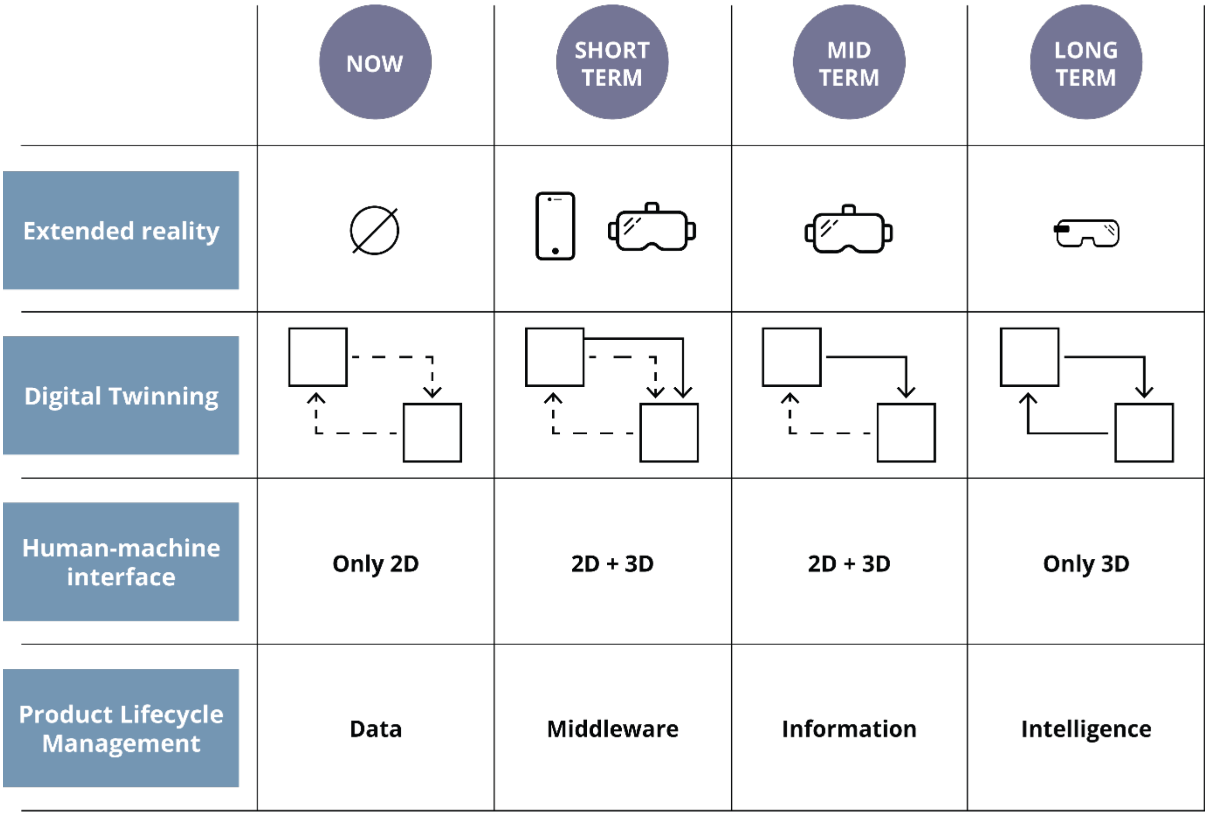

Figure 33: Timeline of technological advancements for remote support

5.3. Use cases & workflows

There are many different use cases and workflows in a production environment. By assessing the available use cases and workflows, combinations that have the most added value and contribute to the strategic plan the most can be selected.

5.3.1. Use Cases

Remote support was chosen as the use case for this thesis. As mentioned previously, other use cases could be, but are not limited to, VR machine training, creating machine understanding or assembling a machine. When looking at the technologies discussed in this thesis, many different use cases can be selected that can fit in the same long-term strategy plan. These use cases can vary in their added value, but they can overlap in the technologies that are used. For example, the use cases remote support and creating machine understanding could both use object recognition to display the information at the correct location. Similarly, VR training and remote support could both have a connection to a remote expert that gives instructions. For each use case, these so-called building blocks can be defined, as shown in Figure 34.

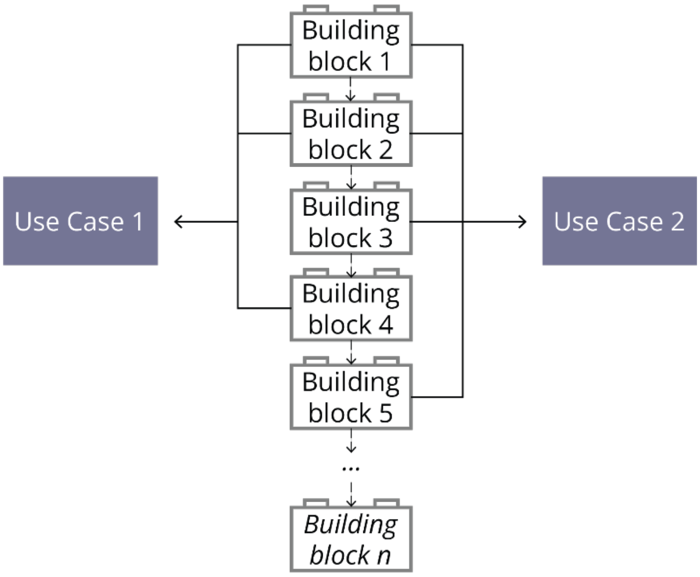

Figure 34: Use cases sharing building blocks

Besides the overlap different use cases have with the building blocks, these building blocks are also interconnected. If one building block has a low level of complexity, the validation of that building block can form the basis of a different building block. For example, if one of the building blocks for VR training is to optimise 3D models for VR/AR, this model can be used for the building block object recognition. Even if the building blocks are not directly linked together, the experience gained from (creating) these building blocks can positively influence the (creation of) subsequent building blocks.

5.3.2. Workflows

To help define the use cases, the current workflows can be analysed. A workflow is a repeatable list of actions. To eliminate as many problems as possible in a workflow, it is key that this sequence of actions is performed consistently. The added value of a use case increases when it can be applied to multiple workflows.

Figure 35 shows two examples of workflows used for the installation of a new machine and troubleshooting a machine problem. These workflows are standard operating procedures at Tembo. It is assumed that similar procedures and workflows are applied at other OEM companies. Remote support could add value to both workflows if applied successfully.

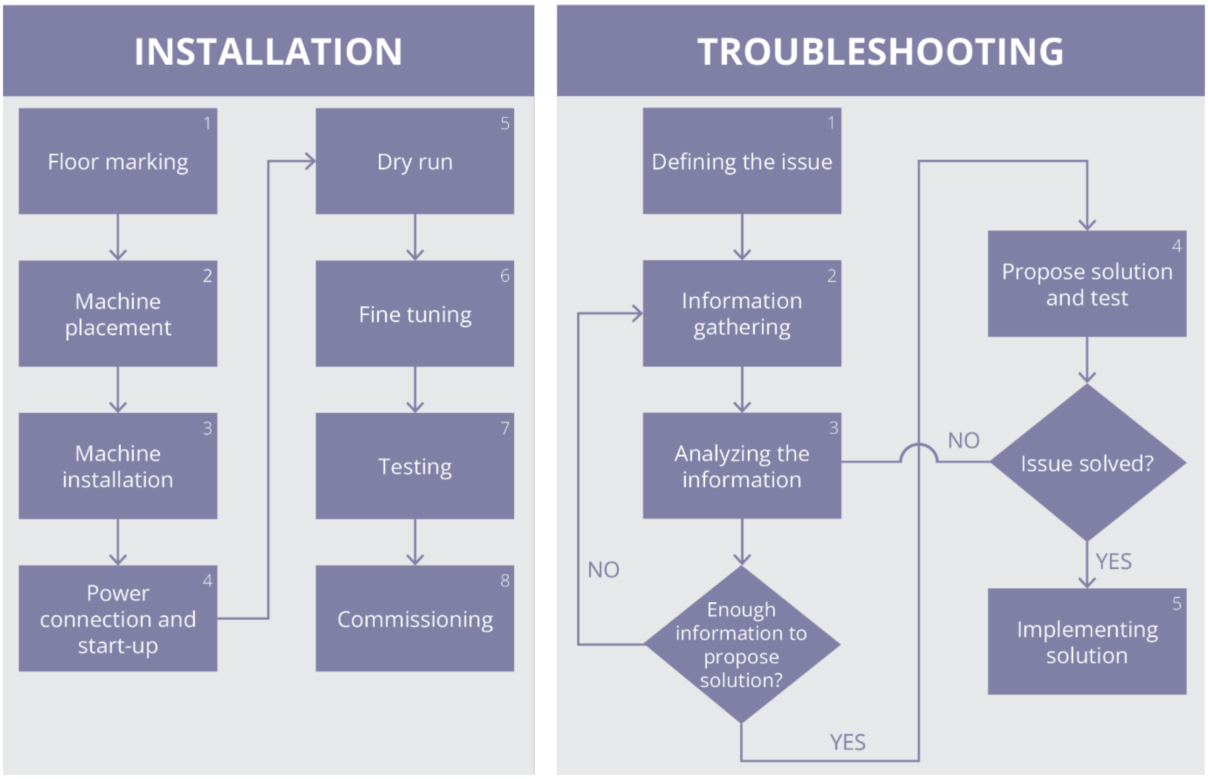

Figure 35: Two workflows, machine installation and machine troubleshooting

There are three reasons why a selected use case can be beneficial. If one or multiple of the reasons listed below is applicable for a workflow, the use case should be considered.

1. The use case reduces the time required
2. The use case reduces the materials required
3. The use case reduces human errors

When the use cases and workflows have been defined, all components can be placed in a roadmap. If there is a change in the use cases or workflows in the future, the roadmap can be adjusted accordingly.

5.4. Roadmap

Based on the available information and requirements, a roadmap was designed. The roadmap assists companies in defining the scope and an action plan for the defined use case and workflows. The roadmap, defined as part of this thesis, is divided into two parts. In the first part, the foundation for the roadmap is made. Here, the strategy and vision are defined, and the technological advancements are assessed. Next to that, one or multiple use cases, along with their corresponding workflow(s), are defined.

The second part is divided between now & short-term and mid- & long-term. The knowledge of today and the expectation of the near future can help scope the project(s), and requirements, as well as an action plan, can be set up. In this block, components that are (near-)certain are placed and developed. For example, as it is assumed the use case will require XR HMDs, XR training is required for all involved users. To create more awareness and input for future revisions, it is strongly advised to create a prototype. This way, the

project becomes tangible for the stakeholders.
In the second block, the mid- & long-term components are placed. As mentioned before, companies need to prepare to step in with their desired technologies at the correct time. If multiple technologies are outsourced, it is important that these components can function together.

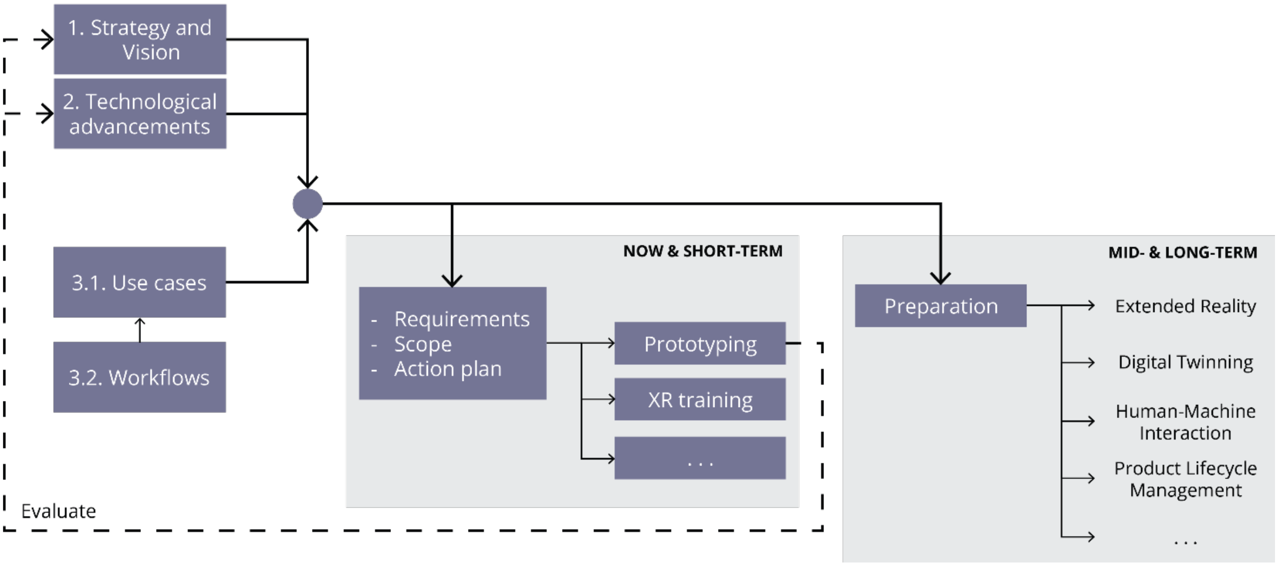

Figure 36: Roadmap for the integration of a use case with new technologies

The roadmap, as shown in Figure 36, should be used as a template. The strategy and vision should be defined without taking the technological aspect into consideration, to keep an open mind on the direction of the company. By assessing the technological advancements and tracking the expected progress of these technologies, the tasks can be divided into short-term and long-term goals.
The use cases and workflows are filled in to define what the requirements are and what the action plan is.

5.5. Verification of the roadmap

Now that the roadmap is defined, it can be verified and validated. For the verification, the requirements set for the roadmap are checked. The roadmap is validated in *Chapter 6. Proof of concept.* For the verification of the roadmap, the requirements that were defined for the roadmap in *Chapter 4. List of requirements* are evaluated. Each requirement is listed below, with an explanation on why this requirement was or was not met.

1. The roadmap translates a vision to a long-term strategy plan

If the use case can contribute to the strategy and vision, a long-term strategy plan can be set up by assessing the technological developments and deciding what technologies require investment of time or money.

2. The roadmap defines the scope of the strategy plan

After the strategy, vision and use cases are defined, and the technological advancements are assessed, the requirements, scope and action plan are set up for the short term.

Iteration is done by evaluating the short-term with the strategy, vision and technological advancements. By iterating often, the scope can be properly redefined when required.

3. The roadmap gives insight in the advancements of enabling technologies

The roadmap forces an assessment on technological advancements. Through iteration, the technological advancements are updated when required.

4. The roadmap aids companies by aligning technological advancements with their strategy and vision

The first step of the roadmap combines the strategy and vision with the technological advancements and the use case.

5. The roadmap can convert a strategy and vision to an action plan

By setting up requirements for the short term and by preparation of technologies in the long term, an action plan is set up and responsibilities can be subdivided.

6. The roadmap must be applicable to any OEM

As the roadmap does not require any particular machine or product as input, this roadmap is applicable to all OEMs.

7. The roadmap allows OEMs to communicate the strategy, vision and action plan with their customers

The roadmap template, as shown in Figure 36, can filled in with the strategy and vision, the technological advancements that are expected as well as the selected use case and workflows. The roadmap is able to see how these components come together and what the required next steps are.

As all requirements for the roadmap are verified, it can be concluded that the roadmap should function as expected. However, to test if it actually functions as expected in practice, the roadmap is validated in *Chapter 6. Proof of concept*.

6. Proof of concept

To validate the roadmap and to show how it can be applied, a case study is carried out. The roadmap, presented in *Chapter 5. Roadmap*, consists of multiple components. These components can be seen as a template. Validating the roadmap means confirming that all these components can be filled in and lead to the desired result. As part of the validation of the roadmap, a prototype is created that shows what remote support could look like. The prototype and the Extended Reality technology have been tested amongst stakeholders. The results of these tests are presented, along with an evaluation of the list of requirements set up in *Chapter 4. List of requirements*. Lastly, the third sub-question is answered.

6.1. Strategy and vision

The strategy and vision for the roadmap were adopted from the general vision of Tembo. As described in *Chapter 2. Analysis*, this vision is aimed at becoming a digital factory and creating a more sustainable manufacturing environment.

6.2. Technological advancements

For the technological advancements of the technologies which are used to enable remote support, the scope was set to the now and the short-term, as shown in Figure 37. This scope was set to match the time scope of the assignment.

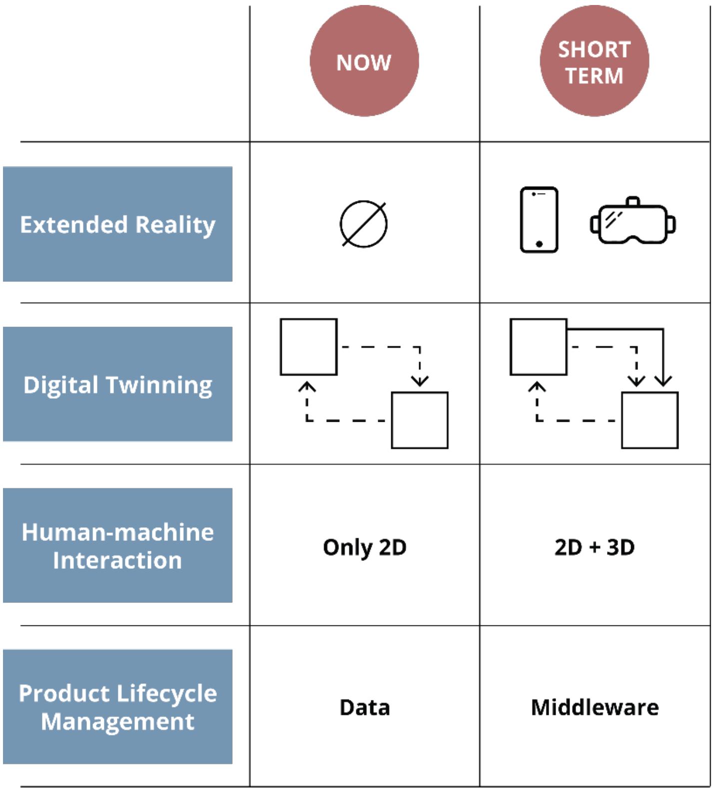

Figure 37: Technological advancements used for the proof of concept

Currently, no XR is used in the production environment of Tembo. The technology was introduced to some employees during previous experiments that were executed by employees of Tembo themselves, but it has not been not adopted yet. The production machines are operated through 2D interfaces, which are attached to the machines. The OEE of the machines is calculated automatically through various sensors on the machines, but most of the digital data is still processed manually.

For the proof of concept, a HoloLens 2 was used (Figure 38). The HoloLens 2 is an HMD manufactured by Microsoft. At the time of writing, the HoloLens 2 is one of the most advanced MR HMDs available and is considered state of the art hardware in industry. As the development tools for this device are not fully mature yet, a mobile device was used for prototype testing. The data that was used was sent manually by the mechanical engineers and the data engineers.

Figure 38: An on-site worker wearing a HoloLens 2 [46]

6.3. Use cases & workflows

As the title of this thesis might suggest, the use case for this proof of concept is remote support. There are many different workflows that could fit this use case. While this increases the added value remote support could bring, it was decided it would be better to choose only one or two workflows for this use case. The workflows that were chosen were problem identification and problem solving. These workflows are important for setting up the requirements, as they define the requirements for what the use case should be able to do. For remote support, the essential building blocks were defined. They are shown in Figure 39.

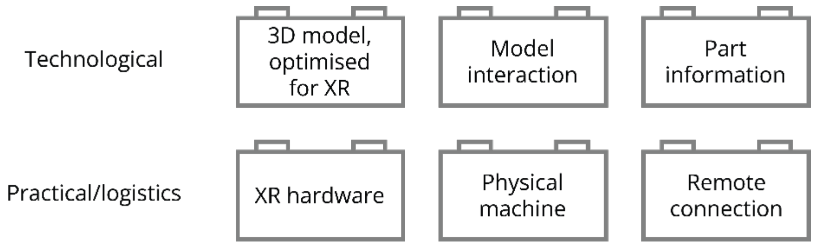

Figure 39: Essential building blocks for remote support

The first part of the roadmap has now been defined and visualised in Figure 40.

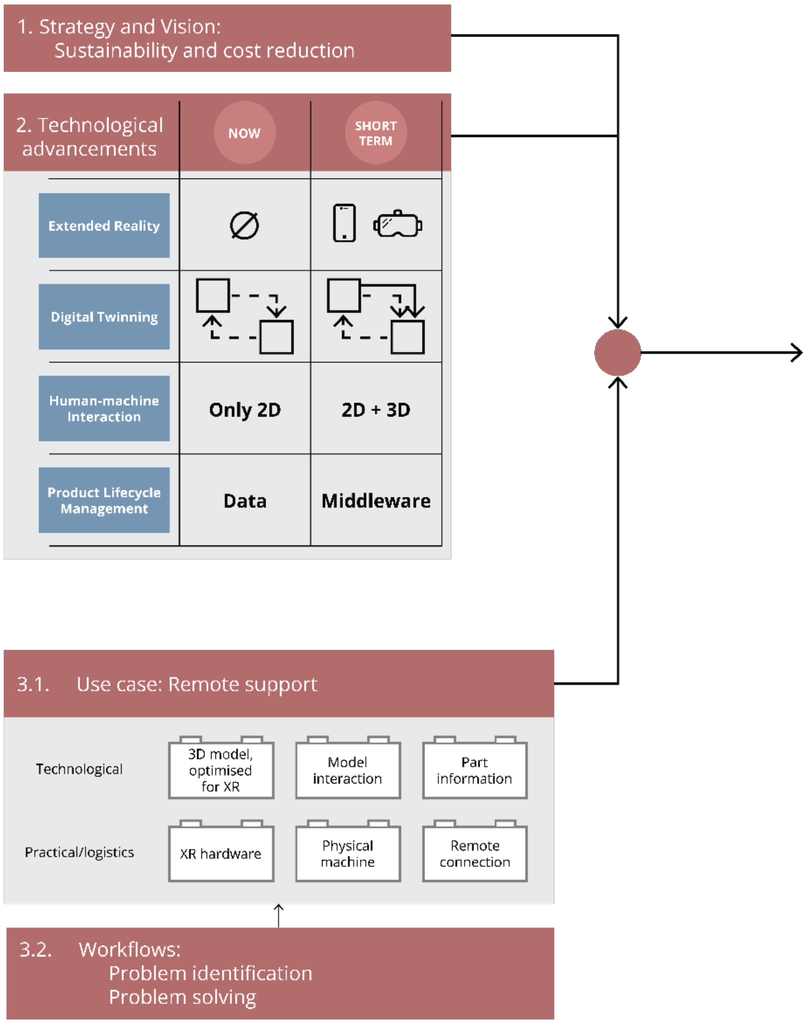

Figure 40: First part of the roadmap filled in

For the second part of the roadmap, only the now and the short-term can be filled in due to the limited time scope of the assignment. In this block, the requirements, scope, and action plan are set up.

6.4. Requirements for the prototype

Chapter 4. List of requirements mentioned two lists of requirements: a list of requirements for remote support in general, and a list of requirements for the roadmap. This sub-chapter will define a third list of requirements for the remote support prototype created during this assignment. For this prototype, the HoloLens 2 was chosen as the XR device. To properly define the requirements for a remote support tool, currently available software on the HoloLens 2 was tested first with stakeholders.

As almost none of the stakeholders had any previous experience with XR devices, the provided Remote Assist application from Microsoft proved a good starting point. Using this application, a remote connection was established from the machine's site to the support staff. It became apparent that without any introduction to the user interface of the HoloLens 2, it was sometimes hard to operate. Once a connection was established, the background noise in the factory became the second issue, because the on-site workers could not hear the remote experts properly. After familiarising with the user interface and connecting noise-cancelling earplugs, the supporting staff was successfully able to draw in 3D onto the machine, as shown in Figure 41. The drawing its position and viewing angle change based on the head movement of the on-site worker, which means that optically the drawing stays in the correct place.

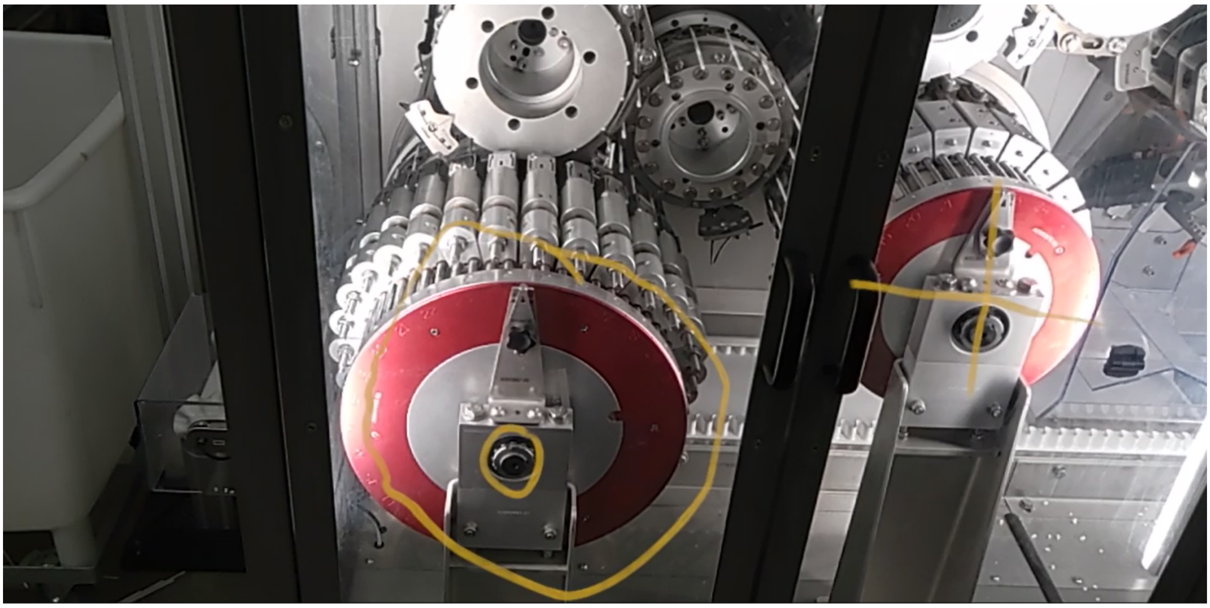

Figure 41: A test drawing onto the machine

A basic functionality was established with the Remote Assist application. However, from multiple tests, the following issues were defined:

1. The connection between the on-site worker and the remote expert was often not stable
2. The reflections of the glass of the production machine made it hard or impossible for the HoloLens 2 to properly track the environment and place the added content in the correct place
3. The drawings were made by hand and thus often not accurate enough

While the first issue is required for proper remote support, it is assumed that in the long term, these issues will be resolved. To find out if there was a significant difference in unstable connections, speed tests were performed, which can be found in Appendix A. However, for the prototype, this was excluded from the requirements.

For the proof of concept, two requirements are set up. These two requirements are meant to eliminate the second and third issues.

1. The application can recognise and localise the machine through reference points
2. The user can accurately select objects

After these two requirements were set up, the scope of the remote support application could be defined.

6.5. Scope

Connection issues were prominent during preliminary testing. Any connection issues during the testing of the prototype could therefore impact the overall experience and opinion of the application. It was therefore decided to create a local application instead of a remote application. The prototype will work with one of the machines of the paper straw production line of Tembo Paper. Instead of a remote expert selecting various machine components, the components will be randomly selected from a set list for this prototype.

6.6. Action plan

With the requirements and scope defined, a prototype will be made with the Unity platform to complete the second part of the roadmap[47]. The digital information that is used for the prototype is collected and functions as the Digital Model of the application. For the remote support simulation, virtual buttons are created for the interaction to simulate the input of a remote expert. In short, the action plan is to create a local prototype in Unity with a created Digital Model. The prototype must include virtual buttons to simulate remote support.

With the action plan completed, the next step is to create the prototype and give XR training to the users. As all components are now defined, the roadmap can be completed. This is visualised in Figure 42. The next step is to bring the prototype to a presentable state, so that it can be evaluated against the predefined strategy and vision, and adjustments can be made. This feedback loop creates an iterative process where improvements can be quickly made without losing the main goal out of sight.

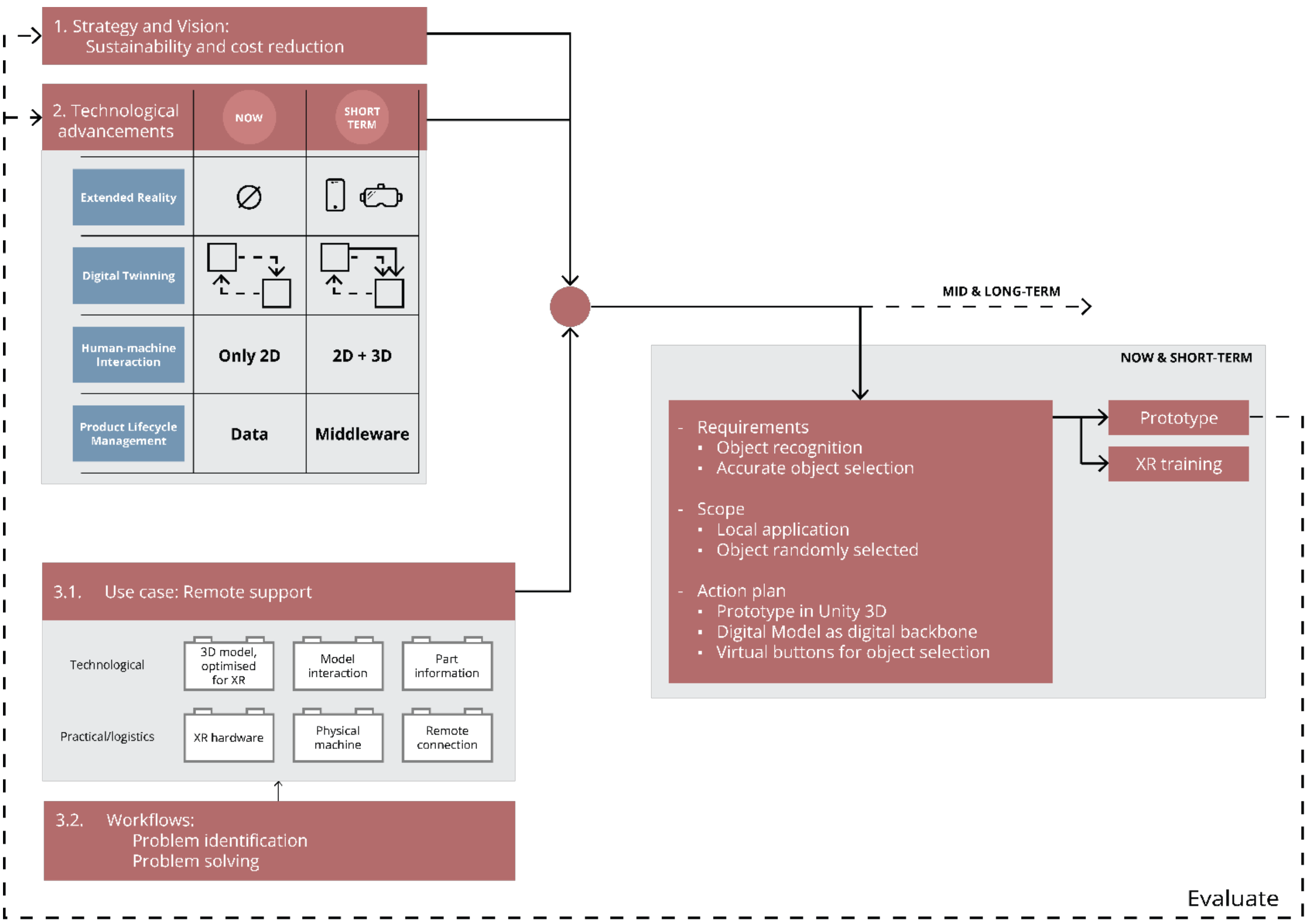

Figure 42: Filled in roadmap

6.7. Prototype

To show what remote support could look like in an industrial setting in the future, a prototype in the form of an application for the HoloLens 2 has been created. This prototype is also tested amongst different stakeholders. Based on the Digital Model, the HoloLens 2 should be able to recognise and track the device. The device is then able to augment digital information to the view of the user, which will be seen as a digital overlay on top of the machine. The user is then able to highlight individual components. Figure 43 shows a visualisation of the prototype, while Figure 44 shows a schematic overview of the prototype [48].

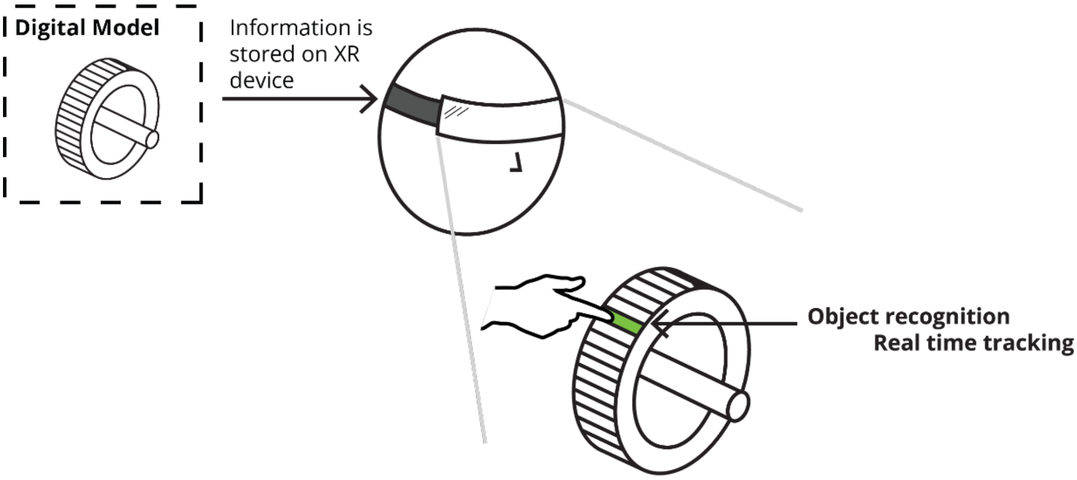

Figure 43: Visualisation of the prototype

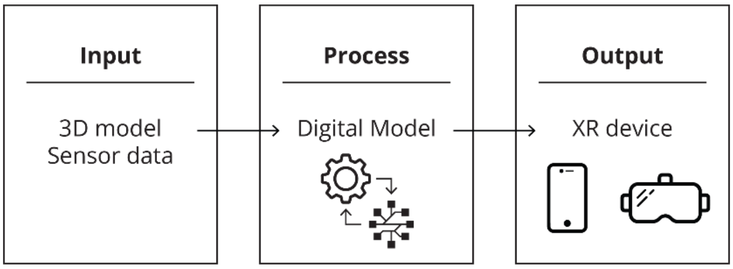

Figure 44: Schematic overview of the prototype [48]

The 3D model of the production machine will be used as input for the Digital Model. The 3D model that is being tracked should be sufficiently distinguishable from other objects, preferably asymmetrical, as that improves tracking speed. Since the tests will be performed on the machines of Tembo, asymmetry is to be expected.

The speed of object recognition can be rapidly improved by providing a Digital Model of the assets that are available to be recognised. The reference for this prototype is shown in Figure 45. Once the machine is recognised by the XR device, it will be possible to highlight modules, components, and parts of the machine. Only several reference points are required to augment the rest of the digital information on top of the physical asset.

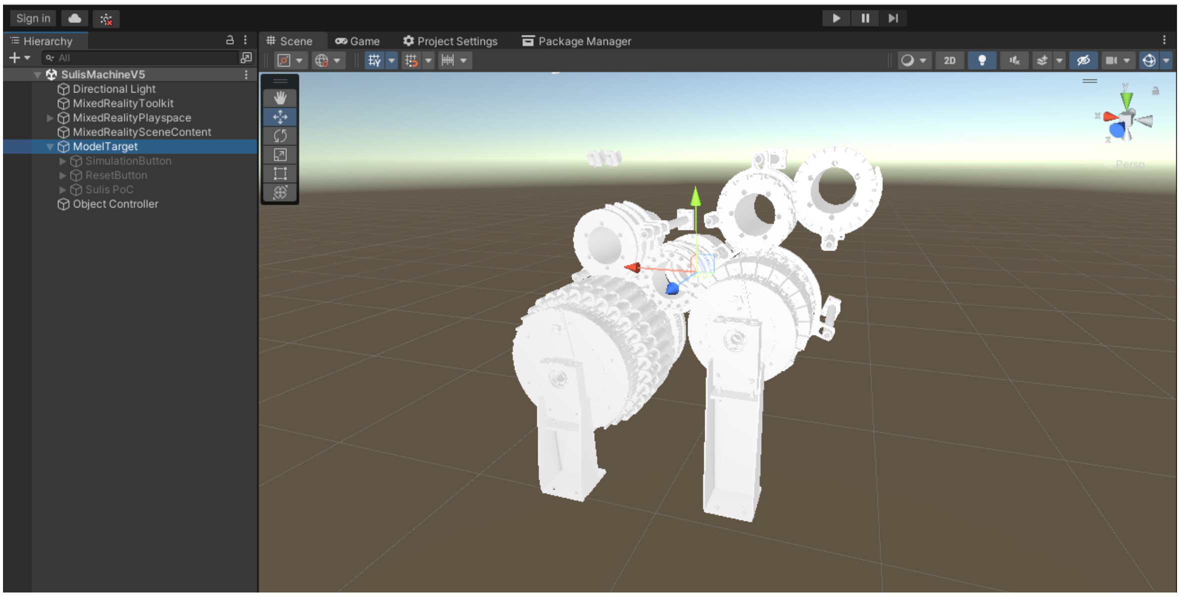

Figure 45: Reference for object recognition

Figure 46 and Figure 47 show the application on the HoloLens 2, just before and just after the reference points were recognised. Once the object is recognised, the rest of the 3D model can be seen. While the rotational position of the cylinders did not match the Digital Model, the machine could still be recognised without issues.

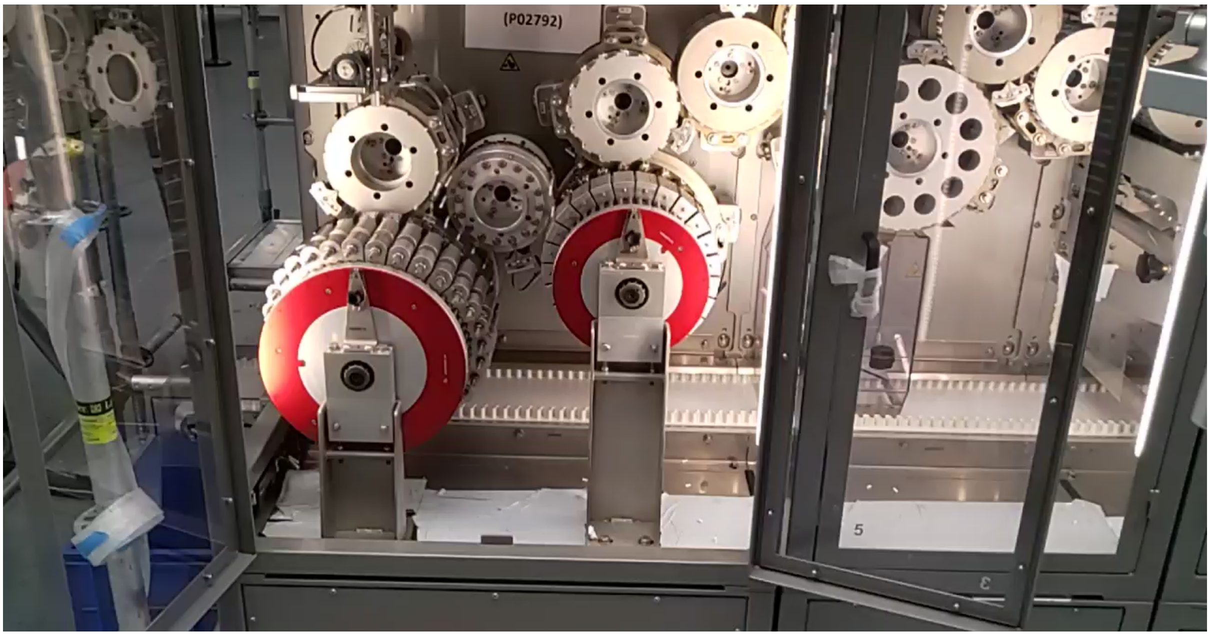

Figure 46: Production machine, just before recognition

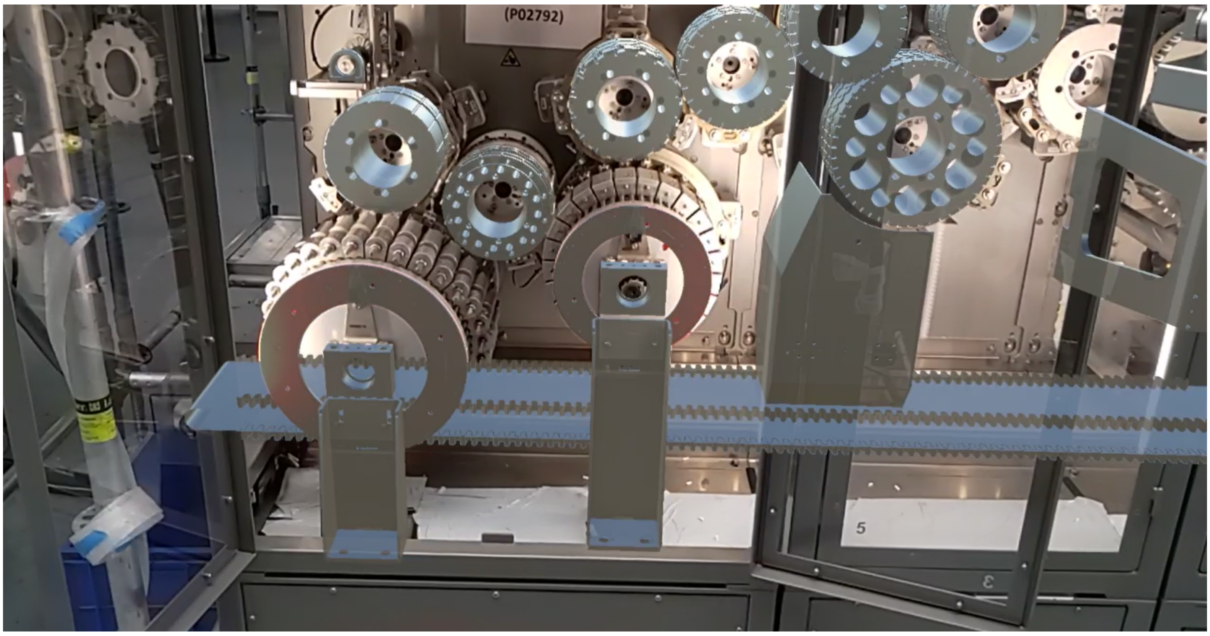

Figure 47: Production machine, just after recognition

Figure 48: Virtual button to simulate remote support

Figure 48 shows the virtual button that was used to simulate the remote expert selecting a component. When pressing the button, a random component from the Digital Model was selected, and its name was displayed in a text frame. As this button is a virtual button, there is no physical feedback from the button itself. The button does not trigger until the finger is a few centimetres past the button, which was not clear to some of the employees during the tests in which they participated.

As shown in Figure 47, the digital information cannot be displayed behind a physical asset. In the case of remote support, this is a positive feature. When the remote expert selects a component, the on-site worker is always able to locate this component, as it is never obstructed by the physical machine. An example of this is shown in Figure 49.

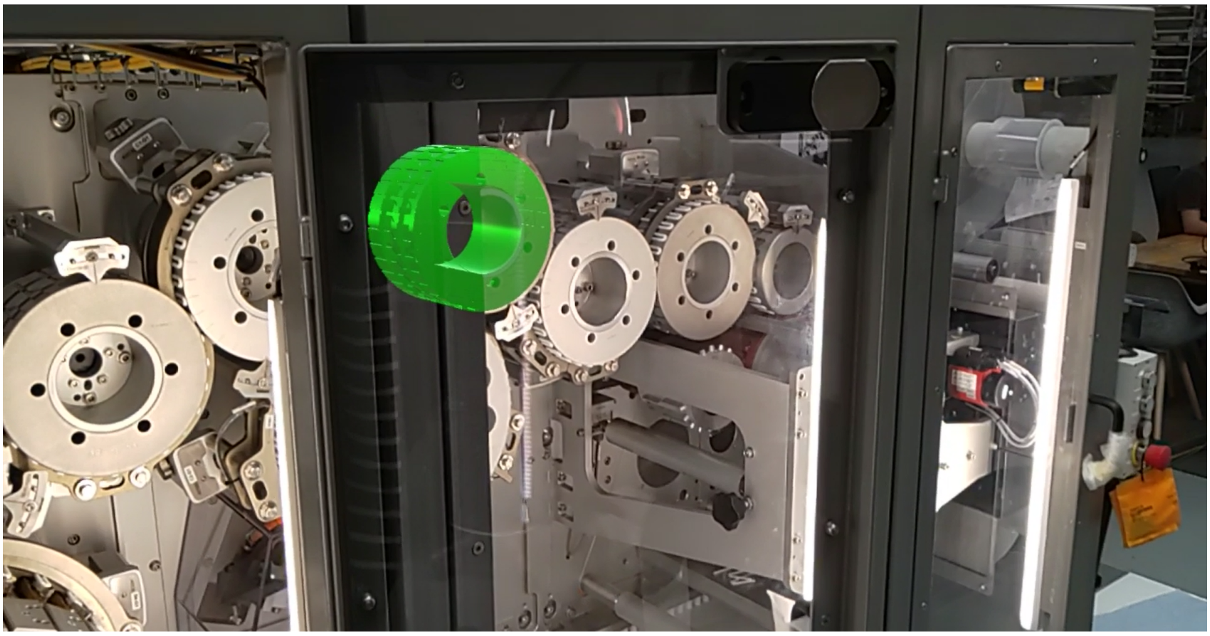

Figure 49: A component is highlighted

The process of creating this prototype can be found in Appendix B. For this prototype, several scripts with different functionality were written. The scripts used to create an applicable file structure from the SolidWorks file, the script used for highlighting components on the mobile application and the script for highlighting components on the HoloLens 2 can be found in Appendix C.

The prototype was tested amongst multiple stakeholders. As this prototype is a local application, the communication between an on-site worker and a remote expert is evaluated using the existing Remote Assist software on the HoloLens 2. A summary of the user tests is found in *Chapter 6.8. Conclusion on the proof of concept*, but a more detailed description of the results of the tests can be found in Appendix D. The second part of the user tests focussed on the communication between an on-site worker and a remote expert. Since a good user experience will raise the chance of adaptation in the future, ironing out issues in the early stage of development is beneficial. Since instructions need to be given on the production floor, instructions were simulated from the remote team to see if the on-site user was able to comprehend and follow these instructions. The user experience was assessed on connectivity, comfort, ease of use, safety, privacy, and potential.

6.8. Conclusion on the proof of concept

The goal of the prototype was to envision what remote support could look like, and to show the employees of Tembo what the current state of the art is. The prototype showed the potential of the technology and it caused a flow of ideas for what else is possible with this technology. Two requirements were set up for the prototype. These two requirements were:

- The application can recognise and localise the machine through reference points
- The user can accurately select objects

The two requirements are met. The machine can recognise and track the machine. The Digital Model enables components to be accurately highlighted. There is little to no chance for the on-site worker to misinterpret the remote expert and vice versa if the Digital Model is used for highlighting the components. The visual indication also eliminates the chance of miscommunication through language barriers.

As mentioned, the Remote Support application and the prototype were tested by different stakeholders. For these tests, the HoloLens 2 was used. The user was only told how to equip the headset, what the basic gestures of the HoloLens 2 are and where to find the correct applications. An overview of the results of these user tests can be found in Appendix E. First, a conclusion will be drawn on each of the categories that were chosen for this test. As mentioned in *Chapter 4. List of requirements*, these categories were selected during the bi-weekly remote working pilot meetings at Tembo. The conclusions of the categories will be followed by an overall conclusion on the user tests.

6.8.1. Connectivity

Overall, the users did not experience any difficulty with remotely connecting to a remote expert through Remote Assist. The main reason was that the connectivity difficulties were on the remote expert's end. The download speed of the HoloLens 2 was sufficient, but the upload speed was insufficient. As a result, the user was able to see the input given by the remote expert, but not vice versa. In most cases, the remote experts deemed the connectivity problems substantial enough to dismiss remote support as a solution in its current state.

6.8.2. Comfortability

The comfortability was tested on the short term (1-15 minutes) and long term (30+ minutes). There was a noticeable difference in the experience between the short and long term. Under 15 minutes, the user rarely experienced discomfort. However, after more than 20 minutes, the users started to experience dizziness and headaches. One user also experienced a blurry digital overlay, which caused strained eyes. The users who previously experienced the predecessor of the HoloLens 2 did mention the comfort was already a significant improvement.

6.8.3. Ease of use

Before starting the user tests, the users were only told about the basic gestures. As mentioned in *Chapter 3.5. Human-Machine Interaction*, the 3D interaction is different and was unknown to most users. All users mentioned that a small training would be sufficient to know the interaction with the HoloLens 2. The prototype was experienced as easy to use.

6.8.4. Safety

There were minor safety concerns amongst some users. Although the HoloLens 2 allows the users to see their environment because of the transparent glasses, the users mentioned that it was sometimes easy to be distracted by the digital content. The users did expect that using the HoloLens 2 more often would decrease the distraction and normalise the workflow.

6.8.5. Privacy

As the HoloLens 2 is equipped with cameras and a microphone, privacy could be of concern. The results of the tests differed per user, ranging from no concern at all to quite concerned. Some of the users of Tembo mentioned that privacy concerns might raise the threshold for the customer to invest in a device such as the HoloLens 2. However, the customer themselves saw no real concerns with privacy.

6.8.6. Potential

When asked about the potential of the technology, all users gave a 4 or 5 out of 5. The stakeholders saw potential for integrating the technology into the production environment from the perspective of their profession. With one exception, all users mentioned they would use the technology again in the future.

6.8.7. Overall conclusion of the user tests

The focus of these user tests was to see how the different stakeholders experienced the prototype, the Remote Assist application and the HoloLens 2 in general. Despite the different professions and therefore different perspectives, the overall experience between the stakeholders was comparable. The main exception for this was the connectivity category, where the service engineers saw issues, while the others did not. At the time of writing this thesis, Tembo is looking into alternative devices. These other devices might not have the same connectivity issues, and therefore might prove to be a more suitable solution for remote support.

The prototype gave the users a good understanding of what components needed to be addressed, and the feedback on it was positive. As each user saw different potential for the prototype from their own perspective, the prototype caused a flow of varying suggestions. Some of these suggestions were additions to the functionality of the prototype, other suggestions were of logistical nature. These suggestions are elaborated on in *Chapter 9. Recommendations.* The last remaining step is to evaluate the prototype with the strategy and vision, and with the technological advancements. The technological advancements only changed slightly during the time scope of this assignment. However, more advanced XR HMDs were announced in the meantime. While the technological difference to the HoloLens 2 is not that significant, competition on the market could decrease the price of XR HMDs. The decrease in prices could lower the threshold for companies to invest in tools such as remote support, which could drive technological developments even further.

The prototype is not in a state where it contributes to the vision set by Tembo. For this prototype, it was never the goal to create a working remote support solution. However, enough input was gained by evaluating to define what the prototype would need so that remote support could perhaps be implemented in the production environment. The envisioned future prototype did still fit the defined vision. There was only one evaluation cycle during this assignment. However, it does not seem the roadmap needs to be adjusted before entering the second cycle, which shows the roadmap is working. From the case study, it became apparent that after setting the long-term vision, this vision was obstructed by the issues of today, which are connectivity and computational power. This can decrease the momentum of development and therefore it loses priority over other projects. On the other hand, the prototype created made the abstract technologies more tangible and caused enthusiasm for the project and feedback for future additions.

6.9. Evaluation of the list of requirements

Now that the user tests have been conducted, the requirements set up in *Chapter 4. List of requirements* can be assessed. The requirement will be marked green if the requirement was met, marked red if the requirement was not met and grey when no conclusion can be drawn yet.

Connectivity

The HoloLens 2 allows for audio-visual input and output. A stable internet connection was unfortunately not achieved. While it was often deemed to work well enough for remote problem identification and problem solving, at other times, the connection was not sufficient at all. A better, more stable connection needs to be in place before a customer's location is applicable for remote support. Because the internet connection was insufficient, the choice was made to work with local applications. Therefore, only a Digital Model was established.

	Functional requirements	Technical requirements
1	The HMD has audio-visual input (8, 9, 10, 13) (From remote expert to user)	A visual digital overlay on top of the real world
		The input of the microphone of the remote expert is sent to the HMD's speakers
2	The HMD has audio-visual output (6) (From user to remote expert)	The information of the camera(s) of the HMD is transferred to the remote expert
		The input of the microphone of the user is sent to the speakers of the remote expert
3	A connection with a digital asset is in place	The remote expert can access the current state (Digital Twin Instance) as well as the to-be state (Digital Master)
4	Both users (on-site worker & remote expert) have access to the right information, at the right time and place	
5	A sufficient internet connection (14)	Download speed above 10 Mbps

		Upload speed above 2 megabits per second
		Latency below 500 milliseconds

Safety

Currently, there are no HMDs that follow the ISO 22000 food standard. The HoloLens 2 Industrial Edition does follow the ISO 14644 clean room standards. While they are similar in requirements, the food production environment requires a ISO 22000 standard, so therefore the ISO 14644 standard is insufficient. Besides food safety, there are also unused opportunities for human safety. The HMD does not yet warn for harmful situations, such as maintenance during production run time. With the design of the human-machine interaction of the prototype, only the minimum amount of information was displayed to prevent distraction. The users also mentioned to not feel immersed to the level that they were no longer aware of their surroundings.

	Functional requirements	Technical requirements
1	The HMD is food safe so that it can be used in a food machine production environment (1)	The HMD follows the ISO 22000 food safety standards
2	The HMD is safe to use for the user and surrounding employees	The immersion created by the HMD should not interfere with the awareness of the user of their surroundings.
		The HMI should only show the information necessary
		The HMD warns for possible harmful actions

Comfort

The head straps of the HoloLens 2 can be adjusted with a small knob on the back side of the HMD. While this allows fitment for a larger range of head sizes, users experienced noticeable headaches.

	Functional requirements	Technical requirements
1	The HMD is comfortable to wear (12)	The user must be able to wear the HMD for a minimum of one hour without discomfort
2	The headband of the HMD can be adjusted to fit different head sizes	A small knob is present on the HMD to adjust the strap circumference

Ease of use

After a small introduction to the HoloLens 2, all users were able to successfully control the device, albeit with some small corrections.

	Functional requirements	Technical requirements
1	The remote support tool is easy to use (10)	The user must be able to successfully use the application after a training of maximum one hour

Privacy

Microsoft Teams was used on the HoloLens 2 for remotely establishing a connection. Microsoft Teams adheres to the ISO 27001 standards [49].

	Functional requirements	Technical requirements
1	The connection between the user and the remote expert is secured	The connection follows ISO 27001 standards
2	The connection between the HMD and the cloud data is secure	The connection follows ISO 27001 standards

While the ease of use and privacy of the currently available technologies is sufficient enough to meet the requirements, the requirements of connectivity, safety and comfort were not met.

6.10. Conclusion

The third sub-question was "How can companies be guided in the decision-making of initiating and integrating remote support?". The answer to this sub-question is a roadmap that was designed in *Chapter 5. Roadmap.* For remote support, there can be many different initiators. This thesis mentions sustainability and cost reduction as the main drivers. As remote support is a replacement for current operating procedures, it is important that the remote support tool is appealing for on-site workers. Remote support integration was tackled from multiple perspectives: long-term strategy, technological developments and the many different use cases and workflows. This made sure remote support could be applied on the shop floor, but would also satisfy on an operational level by aligning remote support with the strategy and vision.

7. Conclusion

In this chapter, an answer to the main question will be given based on the answers of the three sub-questions. Next to that, the list of requirements for general use of remote support will be evaluated in order to draw conclusions about the integration of remote support into a production environment.

7.1. Answering the research questions

The main question, "How can new technologies of Industry 4.0 be used to enable remote support for production machines?" can be answered based on the answers to the sub-questions. The first sub-question was answered in *Chapter 3.7. Conclusion*, the second sub-question was answered in *Chapter 4.4. Conclusion*, and the third sub-question was answered in *Chapter 6.10. Conclusion*.

This thesis is targeted to OEM companies, who already invest or want to invest in new technologies to find sustainable and cost-efficient solutions. To help OEMs with these new technologies for the use case of remote support, an overview is created, as shown in Figure 50.

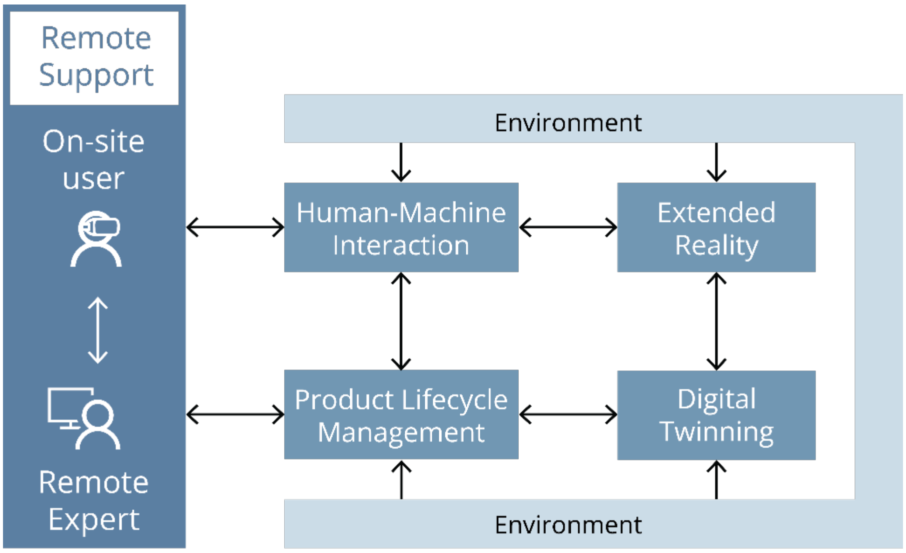

Figure 50: Overview of remote support

Not only does this overview clearly depict how the different technologies are related to each other, the production environment and the users, it is also expandable for different technologies in the future. If current technologies are replaced or if more technologies are added, this overview should be revised to validate the relations between the technologies. To assist OEMs with the long-term integration of these new technologies in their current practices, a roadmap has been created, as shown in Figure 51.

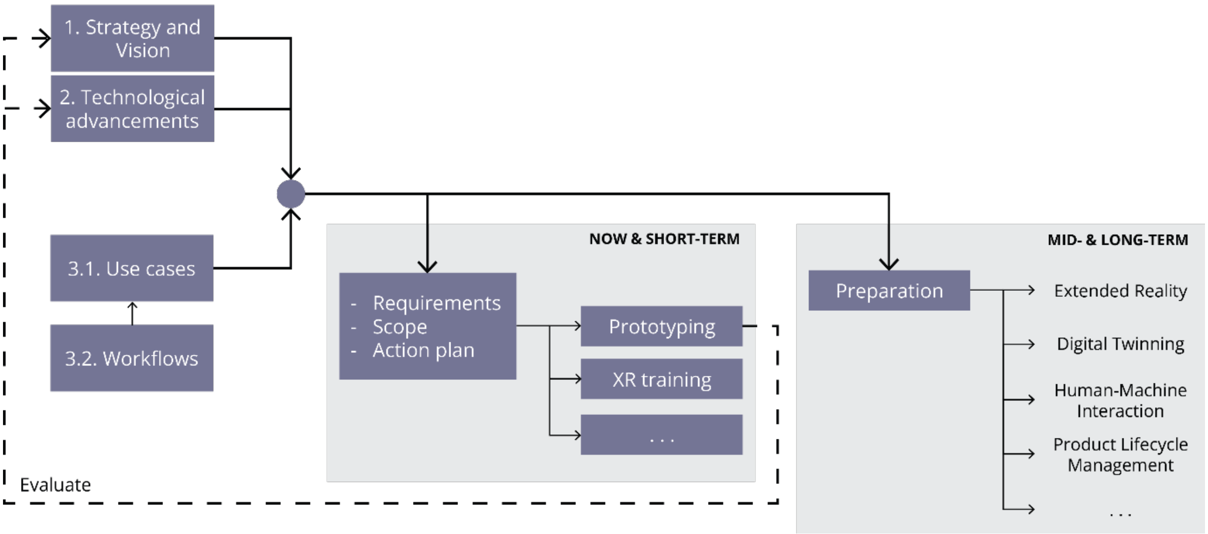

Figure 51: Roadmap for the integration of a use case with new technologies

The roadmap, shown in Figure 51, functions as a template. This has the benefit of being broadly applicable to many different use cases and technologies, which increases the added value of the roadmap and makes it future-proof. The downside is that an abstract roadmap can make it difficult for industry to understand and implement the roadmap. To solve this, the roadmap template was filled in during the use case. This can be used as a reference and confirmation of how to implement the roadmap.

If, as is the case with remote support, the use case is meant to replace an existing workflow, it is important to closely involve the end users of the designed tool. If they are not closely involved, adoption might be difficult as the employees will be able to stick to the old workflow.

7.2. Conclusion on remote support

Remote support is currently in its early stages and is not yet mature enough to be successfully implemented in a production environment of the customers of Tembo.

The hardware required for remote support needs to work well and work reliably. This is especially important for machine production companies, as their customers need to be convinced to invest in the hardware of remote support. As long as there remain issues with connectivity, safety, ease of use, comfortability or privacy, it will be difficult to get (all) customers on board. On the other hand, some field tests were successful and showed the potential remote support has, if remote support matured and the problems are overcome. Investing in Industry 4.0 technologies for a company such as Tembo will pay off. Not only will remote support be feasible, but it will create a better understanding of the entire production process in general.

The roadmap can assist industry with the implementation of remote support in their current production environment. The added value of remote support needs to be clear on both strategic level, as well as on a technical level. Remote support needs to be in line with the vision of the production company, and its use in practice needs to be clear for proper adoption for the users.

8. Discussion

While this thesis is based on literature and a case study at a machine production company, many of the decisions made in this thesis were made on the assumption that technological change will happen. On top of that, the roadmap itself was designed for long-term investment in remote support. Due to the duration of this assignment, only the developments during this ten-month period could be used to extrapolate to create a prediction of the coming years. It could very well be that the developments take an unexpected turn. If there is a lack of technological developments that are required to enable remote support. The roadmap is developed to be adjustable according to technological advancements, and it will keep its relevance as long as this is updated properly. If there is a lack of technological developments, the structure of the roadmap can be reused to investigate other use cases and technologies.

The user experience on Extended Reality as a technology at Tembo was created by the use of a HoloLens 2. Both the benefits and drawbacks of this device attributed to the overall experience of the employees of Tembo. For example, the HMD felt uncomfortable after 30 minutes of use. This experience increases the threshold for using XR HMDs in their field of work, while other XR HMDs might be more comfortable. At the time of writing this thesis the first field tests with a so-called head-mounted tablet, a hands-free head-mounted capturing device, are planned. This device is less advanced, but also lighter and easier to use. Field tests with more XR devices will increase overall awareness, a broader view of XR as a technology, and more inspiration for future use.

9. Recommendations

During this assignment, one use case (remote support) and two workflows (problem identification and problem solving) were chosen. The added value of the roadmap will increase when case studies with more use cases and workflows are executed. On top of that, more case studies are important for the roadmap, as the roadmap can be updated iteratively based on the feedback on implementing it.

One of the main drivers for remote support was the increase in the OEE of the production machines. Even though it has been proven in theory that remote support positively influences the OEE, it is important for companies, and in this assignment Tembo, to explore and validate if remote support is as effective in practice.

From the technology group overview (Figure 52), four technologies were chosen from the first two technology groups. These four technologies were deemed the most essential for the integration of remote support in the current operating procedures and were thus given priority in this thesis. However, the other technology groups can also add value to remote support and should be assessed. Machine learning and Artificial intelligence could help in decision-making, as a suggestion can be given based on experiences from the past. Additive manufacturing could be implemented to automatically 3D print temporary spare parts if there is an unexpected shortage of that part. Robotics could be used for a primary problem investigation, to reduce the number of on-site workers required for problem identification. While a baseline for remote support can be achieved with the technologies assessed in this thesis, other technologies could add different added value. If Tembo wants to continue with remote support, it is recommended that they explore these technologies in the early stages of developing remote support.

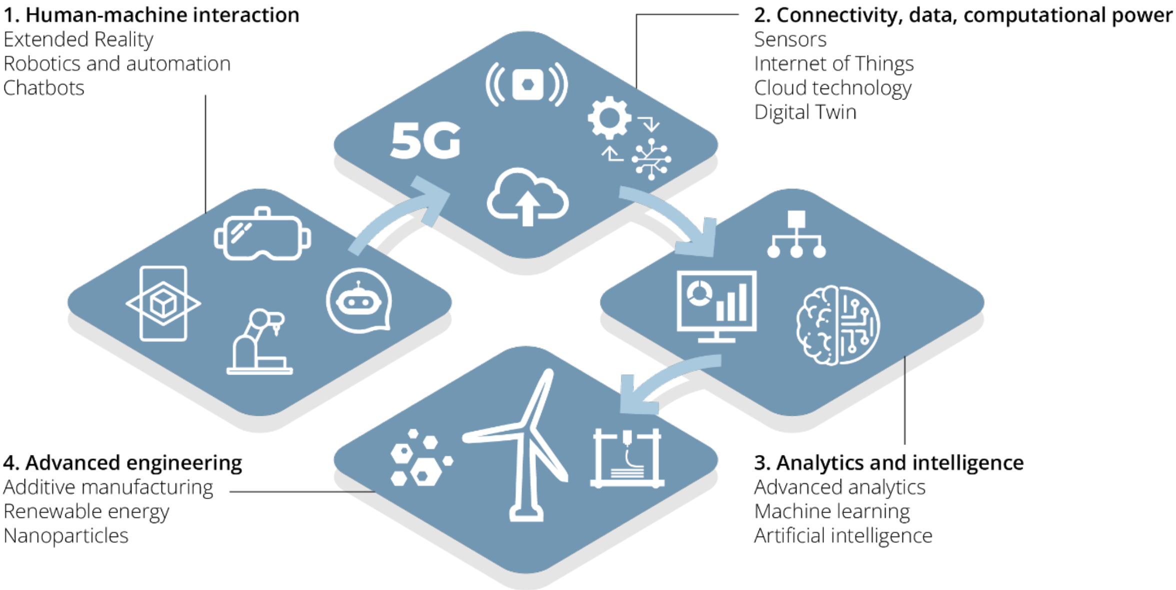

Figure 52: Four foundational technology groups of Industry 4.0, adapted from [24]

The tests during this assignment were done with a prototype, which worked locally on the HoloLens 2, and with the Remote Assist application from Microsoft. For a future application of remote support, it is suggested that an application is created that combines the strength of these two. In this application, the remote expert can remotely highlight components for the on-site worker. A visualisation of this application is shown in Figure 53, and a schematic overview is shown in Figure 54. The schematic also shows which components need to be in place on both ends to create this application.

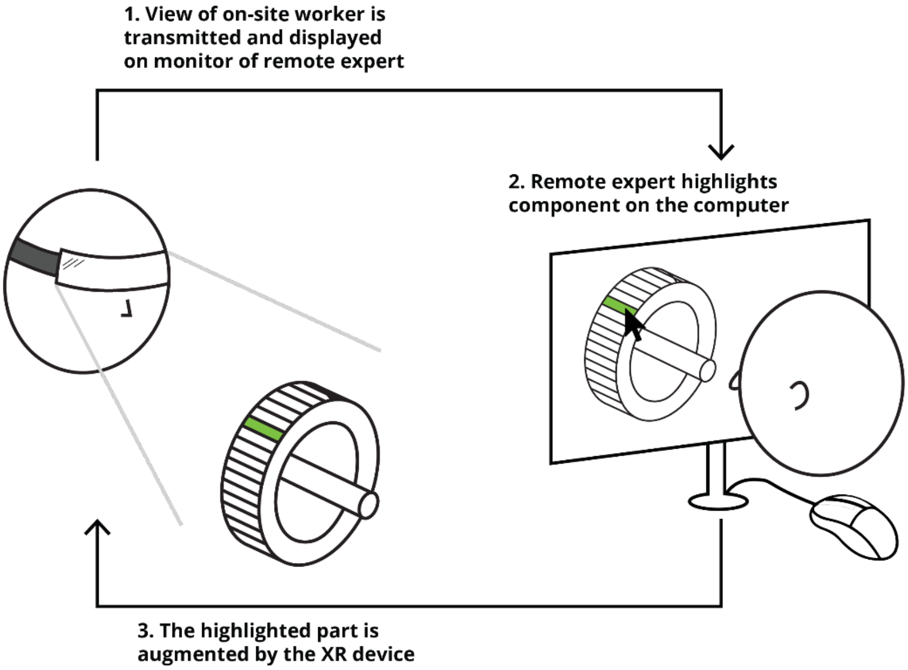

Figure 53: Visualisation of remote support

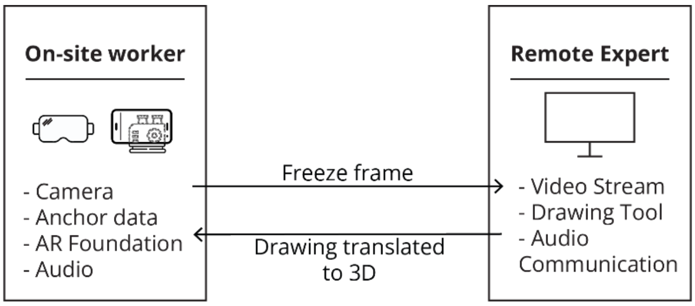

Figure 54: Schematic overview of remote support [11]

Testing the remote support prototype with the employees of Tembo caused discussions on what else could be achieved, not only with remote support but with the technologies in general. The employees that tested the prototype all reviewed the prototype from the perspective of their expertise. This created many different ideas, which can be used as input for future implementation of these technologies.

From the perspective of the Data Engineers, there are possibilities to connect the data from the document management system to a digital interface such as the HoloLens 2. This way, near real-time information could be displayed on top of the machine. With this, heatmaps can be created where problems with the machine are caused, and graphs with the data could be displayed right next to the machine. Another feature would be to select components and create exploded views. Especially with the complexity of the machines, creating an exploded view and zooming in on the smaller, hidden components turned out to be a desired feature. It could also be useful to store the visual feedback from the remote support application to later review or reuse the information. If a machine experiences issues, the log can be used to find out what the fix for it was the previous time. An even more advanced feature would be that the problem is automatically detected based on the data coming from the document management system.

Besides remote support, another use case that was discussed was using XR technologies to train new employees. Currently, employees have to travel to the trainee their location. VR can be used to train employees in a fully immersive digital environment. The building blocks required for VR training were defined and are shown in Figure 55. Some of these building blocks, e.g. 3D model optimisation for XR and XR hardware, overlap the building blocks required for remote support. As VR training was outside of the scope of this assignment, these building blocks have not been validated.

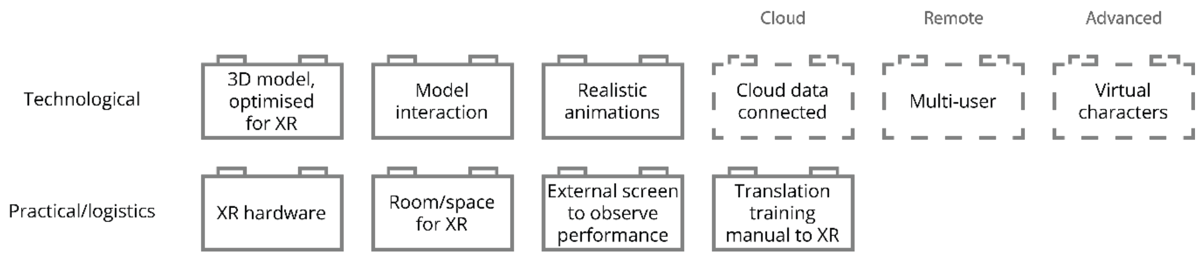

Figure 55: VR training building blocks

The roadmap, as it is designed, follows the assumption that standard operating procedures are followed for the workflows. Only if the standard operating procedures are followed equally by all employees, it can be predicted how a new use case will influence the workflow. However, during the field study it was noticed that employees tend to each have their own way of working, which is often more based on past experience than on the defined standard operating procedures. Ensuring the same operating procedures for all employees will improve the outcome of the roadmap.

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