Master's thesis

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Industry 4.0 and Mixed Reality

Enterprise Modelling for a Learning Factory

Master's thesis in Master in Sustainable Manufacturing
Supervisor: Niels Peter Østbø, Co-supervisor: Per Atle Eliassen
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Abstract

This master's thesis investigates the use of mixed reality in the context of industry 4.0. Within this work, the relationships between industry 4.0, mixed reality and enterprise architecture in inspected from a theoretical point of view.

One of the significant factors hindering the implementation of the industry 4.0 paradigm into manufacturing is the human element. This facet means making sure that the human employees are comfortable in their developing work environments and have the necessary tools to perform their jobs, regardless of their position in an organisation. The most promising technical solution for enabling human employees to work confidently in smart factory environments is mixed reality, the only part of the industry 4.0 paradigm that focuses solely on the human side of the concept.

This thesis focuses on how mixed reality can be used in a learning factory at NTNU Gjøvik. The learning factory is a functioning model of an industry 4.0 system. This work also discusses the issue from various stakeholder points of views for as data that is useful to one person may not be useful for another. Enterprise modelling is used to depict communication between these different elements.

The results of this work are not entirely transferrable to real-life industry 4.0 environments but rather to other universities with similar learning factory schemes. Implementation to real-life involves many elements of this work; however, further studies are needed to make it more realistic.

Preface

Working on this master's thesis has been a challenging but rewarding experience. I have learned more than I ever thought I would. I believe the time and effort spend developing this work has given me skills and knowledge that I will utilise and value in the future.

I want to thank my supervisor, Niels Peter Østbø, for his valuable advice and encouragement, as well as thought-provoking conversations during the development and writing of this work. I also want to thank my co-supervisor, Per Atle Eliassen, for sharing his knowledge, tips and tricks in the field of enterprise architecture. Special thanks go to everyone that participated in the surveys I organised in order to gather data for my models. Lastly, I want to thank my friends and family for their support and kindness throughout my studies.

In Gjøvik, on the 27th of August 2020,
Anna Wilhelmina Vaari

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1. Introduction

Manufacturers have operated in the intersection of economy, society and ecosystems, not in a separate bubble isolated from the rest of the world. The industry has had to change according to the world around it and with new discoveries made. Nevertheless, in the last decades' demands from the outside world have grown exceptionally, accelerating the need for change further. [1]

Customers have higher and higher expectations each passing year, demanding shorter delivery times, very high service levels, as well as customised and personalised products. At the same time, the world has woken into sustainability issues regarding climate change, limited natural resources and social responsibility. [1] Thus, the manufacturing industry requires new means to aid it to meet the various demands set to them by the outside world. These approaches include methods for reduced costs, processing times and resource requirements as well as increased flexibility, productivity and customisation opportunities. [2]

The paradigm of industry 4.0 represents a novel way of organising and controlling value-adding systems in the field of manufacturing. Its core aspects include fulfilling individual customer demands at the same cost as mass production, continuous improvement of resource efficiency, and eventually, the accumulation of new ways to generate value and innovative business models. Thus, the concept influences all areas of manufacturing, from research and development, contracting, order management, production and delivery to the use and the recycling of the manufactured goods as well as customer relationship management. [3]

There are many aspects to be considered in the envisioned industry 4.0 environments and accommodating human workers is a significant part of the big picture involved. It is vital for the realisation of the envisioned future factories that humans are capable and comfortable with working in them, at all organisational levels. Achieving the desired change, however, may require new aspects to education and employment as well as tools to help and guide humans in their new work environments and developing duties. [4, 5]

One set of technologies that has perhaps the most potential for enabling humans to work better in smart factory environments is mixed reality. Mixed reality melds both virtual and real-world environments together [6], creating a reality where physical and digital objects co-exist and can communicate with each other [7]. Mixed reality technologies are in an important role when transforming the data produced by industry 4.0 systems a contextually accessible form for humans. [4, 5]

Industry 4.0 systems will significantly increase the amount of data produced by manufacturers. The appropriately generated, processed and stored data can be made available throughout an organisation and its stakeholders via different advanced technologies and processes. The data can then be used to improve communication between different stakeholders and levels of an organisation. [8] However, the same data will not be useful to people working in different positions and contexts [9, 10]. Thus, it is vital to determine what kind of data different people need.

When discussing ways to make humans comfortable and capable of working in new manufacturing environments, learning factories should not be forgotten. Learning factories have become more prevalent in training students and industry workers as well as to test out a new concept and conduct research. All of this is becoming exceedingly more important considering the approach of a new era in manufacturing. [11]

Finally, it is challenging to implement significant changes in any organisation without comprehensive strategic management and organisational structures. Among the tools to aid in this aspect is enterprise architecture, which details the present and beneficial future states of an organisation’s capabilities, processes, information technology infrastructure, and application systems, as well as data and data flows. It also equips the organisation with a guide for achieving this desired future state from the already existing state. These entities are detailed using an array of standardised representation techniques. [12]

The theory part of this work will define the essential concepts of the industry 4.0 paradigm, mixed reality as its enabling technology and enterprise architecture as a tool for aligning technology with business goals. The methodology section will describe the tools and methods used to complete this work. The results will be presented and analysed in their section. Finally, the results and their meaning concerning the research questions and a broader meaning will be discussed. The work completes into remarks on future work and a conclusion.

1.1. Goal and Scope of the Study

The goal of this study is to answer the following research questions:

1. How can mixed reality be utilised to enhance the use of the cyber-physical learning factory at NTNU Gjøvik?
2. What kind of data do the different stakeholders need from the cyber-physical learning factory at NTNU Gjøvik?
3. Can an enterprise model be created based on these scenarios?

In addition, it is hypothesised that these discoveries related to the learning factory can be transferred to the real world and potential industry 4.0 environments.

Due to resource and time limitations, the stakeholder groups have been limited, and the enterprise model focuses on the use of mixed reality and data flow between the stakeholders and the learning factory. The modelling will be presented not as one large model, but from multiple smaller viewpoints. This presentation technique is chosen due to the limitations of a PDF- or A4-based formats and readability concerns.

2. Theory

2.1. The Industry 4.0 Paradigm

Change has always been a constant theme in the manufacturing industry. These changes are often referred to as industrial revolutions by the scientific community. The first industrial revolution brought about steam- and waterpower and mechanised production. The second industrial revolution introduced mass production, assembly lines and electricity into factories. The development of automation, electronics and information technology systems was the key to the third industrial revolution. The fourth industrial revolution, or industry 4.0, is a still-developing concept, that aims to combine manufacturing environments with advanced digital technologies and change the field dramatically. [4, 13]

Technological developments, complex processes, sustainability issues and customer demands, have increased the need for more optimised and flexible systems as well as efficient methods of quality control and predictive maintenance. These are some of the motivations why the concept of industry 4.0, also known as smart manufacturing [14, 15], has become important in the discussion of the future of manufacturing. [16, 17] The paradigm is a combination of modern manufacturing technologies, automation and data exchange through the industrial internet of things. Cyber-physical systems, smart production, human-machine interaction, additive manufacturing, remote operations, the industrial internet of things, cloud computing and big data analytics are just some of the technologies needed to enable the change to fluent intelligent manufacturing. [9]

The vision of industry 4.0 will digitalise the field of manufacturing, which will act as a basis for many new opportunities. This vision requires integrating all available resources into smart, real-time, self-organised, autonomously optimised and cross-corporate entities. According to predictions, eventually, machinery, production facilities, warehousing systems and global supply networks will be connected as large cyber-physical systems. These systems will exchange data autonomously, prompting actions and controlling each other independently within smart factories. Smart factories have much potential. They can provide methods for optimising decision-making processes, controlling dynamic business and engineering processes or realising individual customer needs. However, many aspects of industry 4.0 are still on the level of visions or prototyping so significantly more research, development and innovation are needed to realise the paradigm of industry 4.0 in the real world. Besides, many of the socio-ethical aspects of industry 4.0 are still unknown. [3]

Ideally, the industry 4.0 paradigm will transform traditional factories into smart factories. It will seamlessly interlink the physical world with the virtual one and allow the adaptive and intelligent control, monitoring and manipulation of the physical world [14, 18]. Hence physical items are managed through their virtual representations. These virtual representations can be used in different functions to support applications that make, for example, highly detailed product customisation, precise and timely logistics supply chains and efficient product delivery possible. [19]

According to Khan et al. (2017), the concept of Industry 4.0 is based on six design principles: interoperability, virtualisation, decentralisation, real-time capability, service orientation and modularity. In this context, interoperability means that different entities of the production and value chains can communicate with each other. Virtualisation means virtualisation of physical processes monitored by cyber-physical systems. Decentralisation is the ability of cyber-physical systems to make independent decisions without any central command. Real-time capability means that the system can collect and analyse data to detect failures and find alternative solutions to solve a problem without disrupting production too much. Service orientation means the utilisation of services of cyber-physical systems, factories and human in the context of service-oriented architecture to facilitate decision-making managers, operators and customers. Modularity means easy addition of new machines, modules and cyber-physical systems without changing the existing modules for the upgrading of factories. [9]

If the production environment can be adequately integrated with the industrial internet of things, it will allow manufacturing companies to build global networks connecting machines, factories and warehouses as cyber-physical systems. These cyber-physical systems will share information and thus trigger different actions. That way, the systems will intelligently connect and control each other. They can be implemented, for example, in the form of smart factories, smart machines, smart storage facilities as well as smart supply chains. These technologies even allow products to exchange data with other components, the industrial machinery, as well as the whole logistics chain. These developments make it possible for the products to make autonomous decisions on the best and most optimised way through the production process. [19]

Developing technologies, changing attitudes and demands by customers are setting new challenges for manufacturing. Compared to the traditional ones, smart manufacturing processes bring resources together in a more intricate manner as well as on a more global scale. [15, 20, 21] It links information and communication networks with resources real-time production and services as well as converts traditional existing fixed production systems into modern web-controlled processes. [9] Industry 4.0 technologies will create new ways of designing future factories as well as more sustainable value chains [22]. In addition to technological developments, the implementation of Industry 4.0 will be influenced by economic and social opportunities and challenges. [14, 18]

2.1.1. Cyber-Physical (Production) Systems

Cyber-physical systems are automated systems that can communicate with each other, which makes them an essential element of industry 4.0 and a crucial prerequisite for smart manufacturing [15]. Consequently, a compound of cyber-physical systems, such as an industry 4.0 manufacturing plant, is called a cyber-physical production system [23]. All in all, connecting cyber-physical systems with production, logistics and services in the current industrial practices, has the potential to transform today's factories into industry 4.0 factories with significant economic benefits [24].

Cyber-physical systems are built of co-operating computational units which communicate intensively with the surrounding physical environment and its constant processes, simultaneously using and providing data-accessing and data-processing capabilities through the internet [3]. Cyber-physical systems are systems embedded with software. They can record physical data by using sensors and directly influence physical processes via actuators. This type of system can also evaluate and save the data it gathers and based on that interact with physical as well as virtual worlds. Different cyber-physical systems can use digital communication facilities to connect and communicate. With sophisticated and safe wireless technologies, the systems can span from local systems to global networks using globally available data and services. Human operators usually interact with these systems through a series of dedicated, multimodal human-machine interfaces. [8, 25]

Cyber-physical production systems divert partially from the traditional automation architecture. The typical control and field levels of a cyber-physical system still include conventional programmable logic controllers close to the technical processes. Their purpose to supply the system with the maximum performance for critical control loops. However, other, higher levels of the system function in a more decentralised way. According to Monostori et al. (2016), cyber-physical production systems comprise of two core functional components. The lower level component controls the advanced connectivity, which guarantees real-time data acquisition from the physical world and information feedback from the virtual world. The higher-level component combines intelligent data management, analytics and computational capabilities that form the virtual world. [3]

In a cyber-physical system, physical and computing processes become very much mutually dependent through fast connection and feedback loops. These linkages and dependencies lead to the seamless merging of physical and virtual (or cyber) components and real-time interaction, making the system interoperable and resilient at the same time. A system like that allows manufacturers to monitor and control physical entities in a reliable, safe, collaborative, robust and efficient way. [15, 20] The reasons behind the evolution and development of cyber-physical systems include their potential to decrease development costs and time as well as product improvement and customisation [14]. In addition to improved process control and monitoring, cyber-physical systems can also improve operational processes. This improvement reduces processing time and increases productivity, which in turn makes the enterprise more competitive and robust against changing customer demands. [20]

The potential of industry 4.0 depends on how well its components communicate with each other. For smooth communication, the components need to have at least two properties. Firstly, a minimum of fundamental communication capabilities. Secondly, to send messages to each other, the components need to be identifiable and addressable by the other components in the production facility. Additionally, an industry 4.0 component needs to be able to operate reliably and securely in the Industry 4.0 system. The components can be practically anything, from the production plant itself and the physical elements within it to pieces of software, processes and even people involved in the production process. Physical industry 4.0 components should be easy to integrate and sturdy enough to withstand high thermal, mechanical, vibrational and abrasive stresses. [3, 13, 21, 23]

Lee et al. (2015) suggest a “5C architecture” for the implementation of cyber-physical systems where the five Cs refer to the connection, conversion, cyber, cognition and configuration, each a level in a sequential workflow [24]. The architecture illustrates the construction of a cyber-physical production system from the initial acquisition of data, through analytics, to the final value creation. Only the first level, connection, signifies the physical world. The next three levels, conversion, cyber and cognition, represent pure cyberspace, or virtual world. The final level, configuration, carries out the feedback from the virtual world to the physical world. [3] If the implementation is successful, the concept of 5C architecture indicates that cyber-physical systems will transform raw data to an actionable form, assist users in comprehending process information as well as eventually adding resilience to the system through evidence-based decision making [20, 24].

2.1.1.1. Reconfigurability of Cyber-Physical Production Systems

One of the current and future challenges in manufacturing is how to take into account the different customer needs while still considering the economies of scale and scope. This factor is especially true in countries of higher labour costs. With high volumes of standardised products, countries with high labour costs are not able to compensate for the inferior cost structure compared to low wage countries with superior quality and productiveness alone. A possible answer to this dilemma is the concept of mass customisation. Mass customisation in the context of manufacturing is a production strategy that focuses on the production of personalised mass products, mostly through flexible processes, modularised product design and integration between supply chain members along the value chain. [3, 8]

As industry 4.0 technologies will enable the more extensive use of mass customisation, at least part of the production line should be able to reconfigure itself via modularisation of the different production equipment. In a reconfigurable manufacturing system, concrete structures and specifications of production processes are replaced by configuration rules, from which case-specific topologies can be derived automatically. Reconfigurable manufacturing systems enable manufacturing companies to adapt to changing production requirements in a cost-efficient way [3]. Machine components can be added, removed, modified or rearranged depending on their mechanical module interface. Within an industry 4.0 factory, products can communicate with their environment and influence the arrangement of reconfigurable manufacturing systems. [8]

In manufacturing, reconfiguring ability enables the adaption to upcoming changes and the production of different product variants at the same time. This flexibility can be accomplished with the help of versatile cyber-physical assembly systems that can reconfigure on physical and software levels. [26, 27] For this modularisation to be successful and economically viable, the organisation of the products' functional elements must be divided into subsystems which rely on each other as little as possible. By flexibly changing the combination of consistent modules, the speed of product development can be increased, and time-to-market can be shortened significantly. [8]

Sensor technology is what enables the flexible production systems and reconfiguring assembly systems. Reconfiguring production lines, for example, can change their setup quickly by reading the sensors on the product part that is next in line to be processed. The sensors carry the information needed to change the production. This way, parts do not need to be produced in batches, but they can be produced randomly instead according to the needs and customer demands of the moment. [22] Modern sensors can even surpass geometrical measurement and scanning and enable the smooth, reliable and fast collection of large sets of data from physical objects [20, 28]. It should be noted that different sensor types gather data in different formats and have different acquisition requirements, which should be taken into consideration in the implementation process. However, sensors that enable advanced and interconnected sensing systems that can only be carried out through the industrial internet of things. [20]

2.1.2. The Industrial Internet of Things

The industrial internet of things connects different machines by adding communication capability into every device to enable them to connect to other devices or access the internet [9]. It is what equips manufacturers with the opportunity to build truly intelligent machines that can fundamentally enhance functions and efficiency across nearly every industrial sector. However, the real potential of combining the industrial internet of things with other industry 4.0 technologies lies in the possibility to build a single architecture that can travel between sensor and cloud systems, interoperate between retailers and cover whole industries. [18]

Large distributed systems cannot be built without connectivity. Human- and enterprise-centric communications are too slow or too infrequently placed to connect large networks of fast devices. The technology to connect the new types of intelligent machines must find the right data and then transfer that data where it needs to go on time. It must be secure, reliable, fast and flexible. Also, only if it can work across many types of industries can it enable the efficiencies of common machine-based and cloud-based infrastructure for the industrial internet of things. [18]

The industrial internet of things controls expensive and mission-critical systems. That is why it has high function requirements. Essential factors to be considered in the implementation of the industrial internet of things are connectivity, ways to identify critical assets and components to collect the right data, ways to synchronise and bridge different sources of data together, as well as conducting an analysis. Two of the requirements are especially vital for the execution of the whole concept. First, it must ensure interoperability by integrating many sub-systems with different designs, vendor equipment or legacy infrastructures. Also, current security systems are not built to handle the vast networks of interconnected components that must trust each other to work efficiently. [18, 20]

According to Schneider and Joshi (2017), the space of the industrial internet of things is so vast that the connectivity technologies do not fundamentally overlap. Thus, it is vital to understand the use cases, architectures and target end-users. That understanding makes it possible to choose the best connectivity protocols for most problems. [29]

Flexibility is one of the most important characteristics used to describe industry 4.0, but a flexible environment cannot be achieved if cables are needed to connect different devices. For this reason, efficient wireless technologies are needed. Building the right wireless network is essential as the physical objects in an industry 4.0 factory use the network infrastructure to communicate with the cloud platform. [19]

The massive amounts of data involved in the smart manufacturing systems require cloud-based applications which in turn demand an excellent wireless network type. For the Industry 4.0 devices to communicate safely and reliably, the industrial internet of things needs a cloud platform that provides five essential services. These include storage, big data processing, topology-related definitions, documentation, and security related issues. [19]

Industry 4.0 processes have unique demands of the used wireless networks, that may render more traditional mobile networks insufficient. These demands include long battery life, low device cost, low deployment cost and full coverage both indoors and outdoors. The problem with these types of networks is that blockage by walls, vehicles, other objects or even people alters the range of the signals by attenuating or distorting the received signal. Besides, different transmitters may try to access the system and get a channel at the same time. If there are no protocols in place to deduce detection and collision avoidance of different transmitter messages, there is a risk of saturating the wireless network. [30, 31] The development of the internet of things has inspired the development of new protocols to serve low data rates, as the system will often require a different approach than more traditional mobile broadband systems. [30]

2.1.3. Data Acquisition, Analytics and Big Data

Implementation of the industrial internet of things will enable manufacturing enterprises to collect data from a growing amount of manufacturing assets. Different resources from machine tools to conveyors and even products will be able to produce diverse sets of data from controllers and add-on sensors, which, in turn, will result in the continuous generation of high-volume data, also known as big data. In a context like that, cyber-physical systems can be developed further to manage big data and take advantage of the interconnectivity of machines to reach the goal of intelligent, resilient and self-adaptable machines. [19, 20, 24]

In the future, the increasing adoption of the industrial internet of things and cyber-physical production systems will cause the amount of digital data generation to increase massively. What was sufficient before will not be enough to distinguish the intricate relationships between the observed parameters due to the size, the dimensionality, and the complexity of the data. Understanding of big data will offer new approaches to collect knowledge with the help of computational tools as well as other methods for data mining, machine learning and other techniques of artificial intelligence. [15, 32] As an example, raw data can be transformed into predictive and prescriptive operations through systems with data management and smart analytics capabilities [20]. However, it will be challenging to handle these massive amounts of data with traditional tools and algorithms. Thus, tools for big data analysis should be developed to make the cleaning, formatting and transforming of industrial data easier. [9, 32]

Sensors have the potential to improve the analysis capabilities of tool, process and product behaviour as well as virtual and numerical based simulation models. The two latter ones are necessary elements in product development to guarantee the capability and robustness of the manufacturing processes. In an optimal situation, sensors would enable product developers to analyse the behaviour of different components and thus make better decisions about the development and production of new products. [33] However, to use sensor signals in monitoring and process control, a control strategy and a model are needed [34].

Issues in manufacturing can usually be divided into visible and invisible categories. With the help of smart analytics of industry 4.0 systems, the more abstract functions can be modelled to make the extracted data more meaningful. As a result, it will be easier to take corrective actions. It can also enable users to understand the invisible relationships between the manufacturing components and make optimised decisions based on that. [20]

The data sets gathered, can be analysed by tools using pattern recognition, reverse engineering, deep learning, data mining and other data analysis approaches. These methods utilise these data sets and reveal correlations between products, processes and operational characteristics that were unknown before. [28] As an example, sensors embedded in different tools can gather process data from the said tools. The gained process knowledge can be used to calibrate simulations, in process control and data acquisition systems as well as cyber-physical production systems. [34] Through analytics of big data will aid to increase the productivity of manufacturing companies. It will allow the prediction of new events, which in turn will offer a solid base for planning new projects. However, not every bit of data will be usable or exciting, nor will all the new insights gained from big data analytics be workable. Thus, it will be a challenge for data scientists to formulate suitable algorithms to extract useful data and insights for use. [9, 10]

The appropriately generated, processed and stored data can be made available throughout an organisation and its stakeholders via the internet. Therefore, the data can be used to improve communication between different stakeholders and levels of an organisation. People with different job descriptions and on different hierarchy-levels and can access information from a different point of view and at different levels of detail. [8] Here lies one of the significant challenges for the industry 4.0 paradigm: data should be presented in a different format to different users for it to be effective. A form that is useful to one user may not be useful at all to another. [9, 10]

Consistent standards for data transfer and utilisation must be applied through the whole organisation and its external stakeholders in order to guarantee the smooth exchange of information. The local accessibility and understanding of global production data are essential for a real-time intervention in case of a changing environment. This standardisation is especially important when considering, for example, the concurrent development of product families and the supply chains and manufacturing capabilities associated with them. [8]

A crucial part of industry 4.0 is real-time access to industrial big data: the sensors, actuators, and other devices in a cyber-physical system demand real-time access to function correctly. Real-time access is also needed to handle smart fault tolerance and failure detection in the shortest possible time. For everything to function smoothly, the bandwidth of the network needs to be fast and unloaded. For example, if there is a delay in the remote controlling of physical devices, it will cause problems for the next physical devices because all the actuators are working in a sequence with predefined time slices. [9]

One way to solve many of the problems involved with industrial big data is cloud computing. Cloud computing can be seen as one of the cornerstones of a well-functioning smart factory. The technology offers a massive data storage space and an extremely scalable computational capacity. Cloud computing systems in smart factories should be time-predictable in order to comply with the real-time demands of the various components of a smart manufacturing system. A potential technology for handling latency requirements of the demanding real-time applications is layering an in-between computing layer known as fog between the factory and the cloud data centre. [35]

2.1.4. Industry 4.0 and Security Issues

The industry 4.0 paradigm comprises of various hardware and software components working together, which can cause severe security risks [9] if the manufacturer does not pay attention to them or take the required measures for reducing the risks. Besides hardware and software security, operational issues should also be considered for safety and dependability reasons. [3, 21]

However, the security issues of industry 4.0 environments are much more complicated than in traditional manufacturing environments due to the interlinkage of physical and virtual worlds. Also, frequent cyber-attacks or hackings against industry do not help the case. Unsolved security issues are one of the major factors hindering the implementation of the industry 4.0 paradigm more broadly to the industry. [21] Besides, industry 4.0 systems can be more vulnerable to natural disasters and power outages, than traditional factories, thus demanding sufficient back-up systems. [36]

The first significant barrier hindering the adoption industry 4.0 security measures is the absence of adequate information security expertise and awareness. The employees participating in the setting up of new solutions are usually familiar with only either information or operational technology security. Industry 4.0 and smart manufacturing environments necessitate security proficiency over numerous areas, for example, embedded systems, network security [31], detecting anomalies due to security violations, the security of complex supply chains as well as security of operation technologies and information systems. It is becoming more and more challenging to find qualified specialists who are aware of the various security issues involved. [37]

Correcting the issue of lacking knowledge requires knowledge cultivation within and across organisational boundaries. The organisations should invest in cutting-edge training on cybersecurity, covering all essential features of the merging of information and operation technologies and smart manufacturing. Sufficient security measures also require funding and commitment from top-level management. Finally, school and university education on the matter will further help in achieving an understanding of Industry 4.0 security among younger generations, thus contributing to long term change in awareness. [37]

Another issue concerning the security of industry 4.0 environments is the fragmentation of current technical standards for industry 4.0 cybersecurity. Wide-ranging initiatives holistically addressing industry 4.0 security issues are lacking. This factor has led to substantial diversities of systems and services security in the manufacturing industry. One possibility of correcting this problem includes the introduction of baseline standards dedicated to industry 4.0 security.

The standardisation actions should be founded on the contribution of the stakeholders in the field of industry 4.0 to guarantee the equal and inclusive representation of appropriate needs and eventually, extensive adoption. [37]

Security deficiencies in industry 4.0 environments are a significant risk to the steadiness of a smart manufacturing company. However, cybersecurity investments should not be motivated only by fear of something going wrong or monetary loss. It is just as essential to consider strong cybersecurity as a business opportunity. Cybersecurity can give a company a significant competitive edge since it leads to having safe, dependable and trustworthy products and services. [36, 37]

2.1.5. Human Employees in Smart Manufacturing Environments

According to the industry 4.0 paradigm, traditional manufacturing components will be replaced with dynamic and intelligent cyber-physical production systems that link physical objects with a digital counterpart through the industrial internet of things. Narrowing the divide between the physical and digital worlds transforms manufacturing facilities into a more adaptive and flexible form, but also requires more wide-ranging skills from the human employees. Interdisciplinary abilities from computer science, engineering and information technology are needed to manage and understand the various interrelations between physical and digital objects. [6]

Despite the evolving automation, the human worker is still recognised as the most flexible entity in any manufacturing system. Humans are an essential part of any manufacturing system, no matter how intelligent or advanced. They must plan, control, manage and troubleshoot. They are needed to provide governance, agility and resilience to the many issues arising in a manufacturing plant. Humans can handle complex operations as well as make flexible movements and decisions, which makes them crucial for manufacturing. Human employees also have expert, often tacit knowledge that can be used to solve problems when dealing with sparse, low quality or missing data. [6, 21, 38, 39]

The paradigm shift of industry 4.0 demands a transformation of attitude in manufacturing environments. Keeping track of the digital information behind the physical manufacturing environment may prove to be difficult first. This challenge is due to digital mechanisms being invisible. Use of cyber-physical production systems requires an understanding of traditional manufacturing engineering but also competences in the internet, sensor and information technologies. Thus, in order to help employees handle the requirements of their new work environments, jobs in production or electronic engineering must be enhanced with interdisciplinary skills from information technology and computer science. [6]

Self-controlling systems communicate via the industrial internet of things and humans, which alters the role of workers towards coordinators and problem-solvers in case of unforeseen events. For example, operators on the factory floor need to be skilled in decision making as the separation of dispositive and executive work voids. Mass customisation increases the need for coordination. Machines will be in charge of more repetitive and dangerous tasks. [2, 8] Job descriptions will most likely change for many people and set new requirements on employees [40, 41]. It is not only personnel on the factory floor that need to understand the principles and paradigms of an arising networked, digitalised future factory. All employees must understand the principles of such a facility and the effect it has on the work they do in order to perform their jobs efficiently. [6]

Fear of changes or the unknown can cause social constructs that hinder the implementation of new technologies to industrial reality. These barriers can be overcome by making employees more comfortable with new technologies as early as possible — this adjustment aids in minimalising the potential fears of workers and managers. However, employees should not be expected to handle these new environments without sufficient training or tools to aid them. Different technologies can be utilised to enable better human-machine interaction. Gamification, mixed reality concepts and learning factories, for instance, are seen promising tools in integrating humans to intelligent manufacturing environments. Mixed reality immensely helps to make the unseen digital mechanisms and concepts of a smart factory more tangible. [6, 41]

2.2. Mixed Reality

As more and more industrial companies move towards smart manufacturing, it is essential to ease the integration of human employees into such systems. While various technologies are essential in realising the full vision of the industry 4.0 paradigm, only mixed and other extended reality technologies are concentrating on improving the synergy of humans and machines and, in this manner between humans and intelligent manufacturing systems. [4]

Mixed reality melds both virtual and real-world environments together [6], creating a reality where physical and digital objects co-exist and can communicate with each other [7]. Mixed reality technologies are in an important role when transforming the massive amounts of data produced by cyber-physical production systems into a contextually accessible form for humans in real-time. Thus, they are the critical enabling technologies for a human-centred approach to industry 4.0 manufacturing as they aid humans within an intelligent manufacturing environment. As an example, the European Union has classified mixed reality as one of the powerful technologies that will propel the evolution of smart factories. [4, 5]

Milgram's reality-virtuality continuum [42] is perhaps the most used concept for explaining the range of mixed reality technologies. The continuum illustrates a spectrum with two extremes, reality, which describes an entirely physical environment, and virtuality, which is an entirely virtual and computer-generated environment (see Figure 1). In-between these extremes is a continuum where a collection of systems that merge computer-generated virtual environments with the real physical environment, also known as mixed reality. [43, 44]

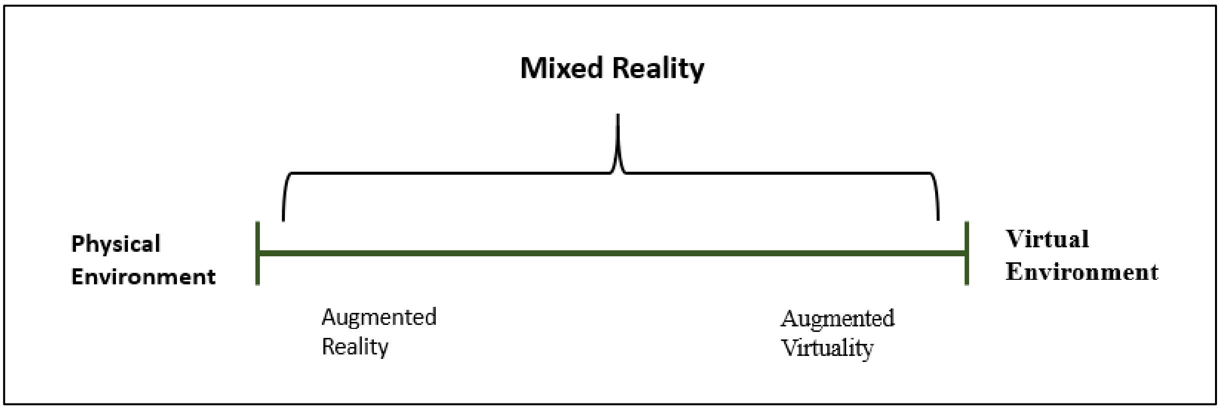

Figure 1 Milgram's reality-virtuality continuum (adapted from [42])

Subsets of mixed reality include augmented reality and augmented virtuality. Of these two subsets, augmented reality is more developed. [43, 44] Augmented reality improves and adds to users' physical environment with the addition of virtual objects. As the opposite of augmented reality, augmented virtuality enhances the virtual world by including content from the physical world into it. Often the line between these two subsets on this continuum blurs. Nonetheless, if the physical content remains dominant, the technology in question is classified as augmented reality. In contrast, for augmented reality, most of the information is shown in virtual form. [4, 5, 45]

If Milgram's reality-virtuality continuum is inspected as a whole, thus combining both entirely physical and fully virtual realities to the concept of mixed reality, the combined result is known with the umbrella term "extended reality". Extended reality refers to all real-and-virtual combined environments and human-machine interactions generated by computer technology and wearables [41]. However, the full concept of extended reality is vast and beyond the scope of this study.

For an application or setting to classify as mixed reality, it must fulfil three characteristics. First, it has to combine both real and virtual content. Secondly, mixed reality is required to be interactive in real-time. Thirdly, mixed reality must be registered, or aligned [46], in three dimensions. [41, 45] Hardware devices are needed to make mixed reality applications and environments visible and accessible for the user as well as to allow the interaction between real and virtual objects. Virtual objects are simulated to generate an accessible representation utilising a display device. Real objects, on the other hand, can be experienced either directly or sampled and transported into a digital model and re-synthesised through a display device. [45]

Mixed reality technologies involve various technological implementation options and hardware devices, and selection of the most suitable one is one of the main challenges for a manufacturing company wishing to implement mixed reality into their organisation productively. [45]

2.2.1. Augmented Reality

As a subset of mixed reality, augmented reality systems allow humans to access digital information through a layer of information placed on top of the physical world [4]. It is a computer application that improves and adds to users' physical environment with the addition of virtual objects. Augmented reality combines digital data, including but not limited to information, images, sounds, videos and interactive objects, with the real world, in real-time.

Users can then observe this through their senses, creating, thus, a mixed reality where both physical and virtual objects co-exist. [5, 40]

The goal of augmented reality is to enhance the users' insight and interaction with the physical world. It simplifies different tasks by supplying humans with digital information, indications and objects about their surroundings that they are not able to perceive directly through their senses. Also, it should be noted that mixed reality is often perceived as confined to the sense of vision. Theoretically, however, it is possible to apply the technology to all human senses. It even has the potential to augment or substitute a users' missing senses by sensory substitution. [5]

Where virtual reality fully engages the users in virtual environments, augmented reality permits the smooth interaction with both the virtual and the physical world through overlaying context-sensitive digital content on the real world [5]. Unlike virtual reality, augmented reality allows the user a view of the natural world while visualising and interacting with digital objects. [7]

Augmented reality is not a new concept [44]. It has been a part of the scientific discussion since the late 1960s. However, recent advancements in computing power and miniaturisation have enabled the development of augmented reality systems with suitable capabilities to consumers and industry. [4] Augmented reality uses these new technological developments and the exponentially growing quantity of data to try and respond to the requirements of modern industry. It tries not just to provide real-time access to the fast-flowing information, but also at the right time and in the right space. At the same time, augmented reality filters the data and presents only the necessary parts of it in a user-friendly and interactive corresponding manner in order to avoid overload of information. [5, 7] Augmented reality technology can be utilised together with other innovative technologies, such as deep learning and semantic web technologies, taking advantage of their respective properties and potentials. Through this combination, the functionality and performance of augmented reality can be improved, gaining better results. [5]

There are some basic requirements for an augmented reality system. These include both hardware- and software-based requirements. The hardware components include visualisation technology, processor, sensor system and a user interface. The software components include a tracking and registration system as well as things related to low latency. [4, 5, 46]

So first, the system needs a visualisation technology, mainly a computer system capable of responding to users' inputs and creating context-appropriate graphics in real-time. Secondly, a processor is needed to control the software that runs the augmented reality system. Furthermore, it connects the augmented reality system to other data sources in real-time. [4]

A sensor system gathers data from the environment [7]. For the significant part of existing augmented reality systems, the key input is one or more cameras. Stereo cameras or ultrasonic, or infrared sensors provide depth perception. In mobile augmented reality systems, mainly head-mounted displays or handheld displays, various sensors, such as accelerometers or gyroscopes, are used to detect the position of the display. [4]

The tracking and registration system is what allows digital objects to be positioned accurately on top of the physical world. Present tracking and registration algorithms are categorised into marker-based, natural feature-based and model-based. The leading technology for this is marker-based, where physical markers are attached to certain places. These augmented reality markers then help to triangulate the right placement for a digital object. This technology well understood, but lighting conditions, mechanical abrasion or dirt can obstruct the recognition of the markers. However, augmented reality applications in manufacturing demand a high level of tracking accuracy. A sophisticated and mature augmented reality system may need a blend of computer vision, inertial and hybrid tracking techniques. Hybrid tracking systems may consist of the use of a laser, RFID and other types of sensing devices. [4, 7, 46]

Despite the growing maturity of augmented reality systems, there are still many challenges and unanswered questions related to augmented reality, both hardware and software related. The main technological issues include process speed and ergonomics. On the other hand, the most significant issues in the software side include user feedback, tracking technology, and integration of the augmented reality systems with advanced information technology systems, such as a visualising shop floor management information. [4, 47]

2.2.2. Augmented Virtuality

Augmented virtuality comprises of a more advanced level of virtuality than augmented reality. Due to this fact, a more substantial proportion of its elements are synthetic. The technology is currently used for the visualisation of new products and visualisation of different procedures as well as marketing and sales. [41]

Augmented virtuality is the lesser developed and researched part of the mixed reality spectrum, and it does not have as many products on the market as augmented reality does. However, Microsoft HoloLens is classified as mixed reality glasses. Besides, augmented virtuality is gaining more and more attention, and several new mixed reality glasses have been launched to the market in the past couple of years. [41]

2.2.3. User Interface

Technological advancements have led to a significant increase in the processing power and storage capabilities of devices. These smart devices are embedded with different types of sensors and actuators and can thus communicate, connect, and interact with each other through the internet. Because of these properties, computer systems and smart devices can quickly retrieve, store, process and display extensive amounts of heterogeneous data while needing minimal computational power and storage space. These capabilities make the real-time digital description of information possible, thus creating a more effective way of interaction and augmentation. [5]

Ideally, augmented reality allows users to interact with information in manufacturing processes directly and intuitively. It also lets the users utilise their natural spatial processing abilities to gain a sense of presence in the physical world with virtual information. Hardware has become significantly smaller and more powerful. In contrast, various efficient and robust algorithms have been developed to provide a quicker response as well as enhanced accuracy in tracking and registration. [46]

The user interface should be a display capable of combining real and virtual images and a tracking system capable of determining users' viewpoint position. [5] An augmented reality user interface allows two-way communication between the user and the system. Force feedback [41] and acoustic cues are some of the technologies used to achieve this. Many augmented reality AR applications use force feedback to improve the user's more immersive experience [46]. Notable methods for user input include gesture or speech recognition, the direction of gaze and discrete hardware solutions. The last-mentioned can include anything from mouse and keyboard to hand-scanners. [4]

There are two conventional methods for depicting three-dimensional volumetric data: surface rendering and direct volume rendering. Surface rendering is a binary process that visualises the surface meshes at tissue interfaces that are typically preprocessed by segmentation and embody only a small portion of the raw volumetric data. Direct volume rendering, on the other hand, is an unceasing and significantly more computationally intensive process that involves the full volume of data. However, it provides the most precise visual three-dimensional representation. Augmented reality displays work in combination can with either of these methods. [7]

There are various display technology options for augmented reality. [40] The various subtypes of augmented reality devices include handheld displays, head-mounted displays, as well as projectors and fixed displays [4]. Further subtypes of these classifications are optical see-through and see-through video displays as well as monocular and binocular displays. Optical see-through displays grant a direct view to the surrounding environment through special transparent lenses, also called optical combiners or holographic waveguides. Video see-through displays, on the other hand, use a video feed to view the surrounding environment indirectly. Furthermore, monocular displays supply only one sole channel for viewing, while binocular displays supply two separate channels, one for each eye, to replicate the perception of depth through stereo imaging. [7]

Optical see-through displays have three main components: computer, optical combiner and light engine. The optical combiners fuse digitally generated content with light from the natural world. The optical combiner acts basically in the way of a partial mirror, permitting light from the real world to pass through while redirecting light from the projector to create a hologram. [7]

The main benefit of augmented reality displays is that they can place and anchor digital objects wherever in space, which can be useful in many ways. Still, it can also inadvertently deter the view of critical physical objects, such as the user's hands or tools. Accordingly, the manner of visualisation of digital objects in front of and behind physical objects, also known as object occlusion, will be crucial for managing digital content in settings where the operator needs to take action, for example. [7]

Other issues in current augmented reality displays include the field of view for augmentation. Usually, the binocular field of vision of the human eyes is approximately 200º in the horizontal plane and 135º in the vertical plane. Each commercially available optical see-through, head-mounted display has a horizontal or vertical field of vision that is less than 90º, with most ranging from 30º to 40º. Also, most untethered augmented reality displays have battery lives of two to three hours, a crucial aspect to consider during extended use. [7]

The arrangement of augmented reality settings requires four crucial elements. These elements include target places, augmented reality contents, tracking module and a display system. Essential parts in forming an augmented reality environment from the end-user viewpoint are intuitive observation, informative visualisation and immersive interaction. These properties are used to integrate augmented reality technology and develop custom-built three-dimensional simulations. [46]

Each type of interfacing device supports different fields of application and has specific hardware and software components. In choosing a suitable type of device for a specific situation, multiple aspects should be considered. These aspects include but are not limited to, the type of mixed reality used, environmental conditions and user comfort as well as the type of work the device is supposed to help the user. As an example, only entirely voice-controlled smart glasses, allow handsfree working, which is ideal for training directly at the workplace or dealing with complex hands-on maintenance. The use of a device in a factory setting, where it can be affected by dirt, moisture, shocks or heat, for example, has amplified the requirements on the sturdiness of the device. [40]

Furthermore, augmented reality headsets are becoming more and more popular, having entered the consumer market. Augmented reality headsets work as handsfree interfaces making it easier to carry out tasks in the real world. Some examples of augmented reality headsets currently on the market, include Microsoft HoloLens, Meta 2, Magic Leap and Vuzix Blade. [5] Nevertheless, these head-mounted displays are often perceived as uncomfortable and may cause dizziness and headache, especially after extended usage. Thus, a lot of the research in augmented reality applications leans towards the use of handheld devices. The benefits of handheld devices, such as a touchscreen, a high-resolution camera and a gyroscope, have already embedded in commercial smart mobile devices. The use of standard smartphones in augmented reality applications is increasing. However, due to the limited processing and storage capabilities of these mobile phones, some researchers use a client-server architecture to improve real-time performance. [40, 46]

Augmented reality displays demand a very low latency in order to keep the virtual objects in a steady position. A big part of alignment errors originates from the variance in time from the moment a user moves, and the time it takes for the corresponding image to the new position of the user to be shown. This time difference is known as end-to-end latency, and its quality can cause substantial changes to the observed scene. Research suggests that the objects should not shift more than 0.25 degrees between two frames. As an example, if the user rotates their head 50 degrees per second, latency should not be more than five milliseconds. This requirement can be met via a mixture of numerous levels of position and orientation tracking. It demands diverse relative and absolute accuracies, combined with different levels of rendering to diminish the three-dimensional data to moderately simple scenes so that the three-dimensional data can be rendered quicker. [46]

The recent advances in mixed reality technologies have gained much attention in recent years and made its more extensive utilisation in the real world, both commercially and industrially, possible. Prominent technology companies are competing to introduce new and better mixed reality hardware in order to ensure their share of a growing market. [43]

2.2.4. Mixed Reality in Manufacturing

The development of more intelligent manufacturing systems will most likely transform work into a more flexible form, location-, time- and content-wise. As such, decision-making skills, interface competencies, and the ability to solve abstract situational problems will become more significant for all employees. The new developments set up new demands in education and training in the workplace to fill the new demands the technology sets for employees. Besides, the integration of digitalisation into a manufacturing company requires modifications in all areas of the organisation, from production to human resources. Digital support systems, mixed reality technologies, in particular, are a way to both improve the manufacturing processes themselves as well as an inventive way for practice-oriented learning. Use of mixed reality aids the work of the employees by supplying data on-demand on a context-specific basis and enriching real-time situations with targeted information. [40]

Mixed reality can be used in many ways in manufacturing. It can be used for information visualisation, human-machine-interfaces, remote collaboration [43], design tools as well as education and training. Strategic goals involved with the adoption of mixed reality technologies include improvement of manufacturing processes, improved training methods and shorter development cycles. The better deployment of instructions and manuals and customer service can enhance the end-user experience. From a product development perspective, mixed reality can allow a more fluid collaborative design as well as work through the inspection of digital prototypes. It will also help new employees to receive training specific to their jobs as well as health and safety training. Assembly instructions will help the people working at the assembly line and augmented operator manuals will help the operators, which could prove to be especially important when the production facilities are turning more complex. [48]

Augmented reality enables both the improvement of industrial processes and learning processes. As an example of an industrial process application, it is possible to test which process steps can be improved by augmenting along the entire value chain. By supplying on-demand, context-relevant information independently from a location, lead times can be shortened, and activities that add no value can be trimmed down. For the learning processes, on the other hand, augmented reality devices signify a way of learning that allows new learning scenarios. [40]

Mixed reality is also useful in making the learning content more engaging for the students, trainees, or new employees. Through the technology's enablement in long-distance learning, a new employee can, for example, familiarise themselves with their new work environment from home, before their first workday, to make the transition to a new work smoother. Mixed reality is also able to improve the efficiency of tasks by adapting to the user's experience level. [45]

Augmented reality systems help in preventing errors in the manufacturing process. It protects against human mistakes, which is valuable for manufacturing companies which desire maximum quality. [44] The ability of an augmented reality system to give immediate feedback makes it nearly impossible to assemble wrong and result in high quality. This ability supports the use of augmented reality in more advanced and more extended tasks within manufacturing, for example, elaborate set-ups, operations with various tasks or long cycle time as well as advanced maintenance. [41]

Maintenance is essential in guaranteeing high equipment performance, the decrease of downtime and interruption to production schedules. However, the growing complexity of equipment presents significant challenges to the maintenance staff. These challenges in mind, advanced information technologies can be used to support maintenance. For example, various maintenance activities can be improved with the use of augmented reality. Augmented reality can often be a smoother approach for supplying maintenance information than full paper and computer-based manuals. Augmented reality can also enhance the workflow of maintenance operations. [46, 47]

Industrial settings are very complex and challenging, so implementing augmented reality to such settings will be equally challenging. According to Syberfeldt et al. (2015), a crucial factor for the successful implementation of augmented reality in the industry will be its acceptance by the workers. There are four critical factors in the acceptability of augmented reality systems by the workers. [44]

First, the task that augmented reality is supposed to help a worker with should be complicated enough; otherwise, the user may feel that that it is not worth using the augmented reality system. Secondly, the augmented reality system should make the user more efficient; otherwise, the user may not find it useful. Sufficient training of new users is also vital in order to ensure that they use the system most efficiently. Thirdly, a system that comes without flaws is significantly more straightforward to accept than a system that contains apparent imperfections. Building a perfect system is, of course, nearly impossible, and it becomes even more challenging when it comes to augmented reality as the enabling technologies are not yet fully mature. Lastly, when introducing augmented reality to new users, the system and all its advantages from the user's perspective should be engagingly presented and explained. [44]

Mixed reality has the most potential of the extended reality technologies on manufacturing settings as it can be used in most phases of manufacturing. It is not as immersive as virtual reality technology, and thus, it gives a better user experience in settings where the user needs to be aware of their physical surroundings. However, mixed reality technologies need further development before they can work flawlessly in industrial environments. [41]

The industrial application of mixed reality, and augmented reality, in particular, is not as common as the equivalent social and entertainment applications. This difference is mainly due to the stricter requirements in tracking and registration accuracy and sufficient alignment with traditional practices. Also, when playing an augmented reality game, the user can quit any time and restart at will. The same is not necessarily possible for engineering users, who may be expected to spend a significant amount of time using the system in their jobs. Thus, ergonomics, human factors and cognitive strain are essential factors to consider, when designing a mixed reality system. [46]

Mixed reality technologies have massive potential in the field of manufacturing. However, it is up to each organisation to determine how and when to utilise them. In order to develop more knowledge in this issue, more practical experience and knowledge need to be built up within different organisations and research communities. One way to do this is to test technologies in a learning factory. [41]

2.2.5. Mixed Reality and Digital Twin

The goal of industry 4.0 and cyber-physical systems is to connect the physical world and the virtual world. This linking between the physical and the virtual world gives manufacturers the ability to create and update real-time virtual representations of physical objects to form digital twins. [14, 49]

The purpose of a digital twin is to simulate and reflect a component's state and behaviours through modelling and simulation analysis and to predict and control their future states and behaviours. Since the status, behaviours, and properties of the physical world change frequently, multiple types of data are being produced, used and stored from the production processes until the disposal of a product. A digital twin tries to bring consistency to this changing environment by combining whole elements, even entire enterprises as well as process data. If cloud technologies can be stored in digital twins through the industrial internet of things, it can ensure the scalability of storage, computation and communication. With thorough implementation of the paradigm and through mapping each object in the Industry 4.0 facility, entire production plants can have full representations in cyberspace. [13, 15, 19]

According to Rasheed et al. (2020), the development and implementation of digital twins will diminish the separation between humans and machines even further. This development will demand even faster, more and more effective communication and interaction capabilities from the surrounding systems. Thus, mixed reality will be needed to create detailed visualisation of the resources as well as to allow better communication and interfacing between humans and digital twins, among other enabling technologies. [50]

2.3. Learning Factories

The fast development and interlinking of both information and communications technologies and production engineering have led to the creation of cyber-physical production systems. These developments form a significant future trend in industry and research and are referred to as industry 4.0. Without a doubt, these new technological developments will require new skills for employees. [51] However, it is not only the technological advancement that sets new challenges for the industry. Also, globalisation, changes in demographics, shorter product cycles, a higher number of product variants, resource efficiency ambitions and sustainability demands are some of the significant factors manufacturing companies need to take into consideration. [52]

Learning factories have existed in some form or another for several decades [11]. The concept first gained more interest with a more widespread desire to integrate engineering education with knowledge and hands-on training to solve problems in real life [52]. Later on, learning factories have served as testbeds for enhancing manufacturing education, research and training by adopting real industrial practices into the learning factories. [53]

For many nations, manufacturing has been and still is a crucial wealth-generating activity. For example, in Europe, the manufacturing field forms more than 21 % of the gross domestic product. Thus, it is vital to address and new challenges and take them into account in manufacturing education and research. The competency-level of employees plays a crucial role in dealing with all these challenges accordingly. Contemporary concepts of training, industrial learning and knowledge transfer schemes are needed to enhance the overall performance of manufacturing. These new concepts need to take into account that manufacturing as a subject cannot be taught proficiently in a classroom alone, and industry can only evolve through the adoption and implementation of new research results in industrial operation. One way to address these issues is through learning factories. [11]

Learning factories link theoretical and practical knowledge, providing a practice-oriented side to engineering education. They are not solely for the pure engineering sciences either but can combine elements from fields like design, prototyping, manufacturing as well as business and economics, thus serving students, researchers and industries with diverse backgrounds. Learning factories offer a shared platform for industry and universities to collaborate for mutual benefit. There are various learning factory projects around the world, varying from one another in orientation and design of facilities, but most of them have a similar approach and concept. [11, 53]

The current widely accepted purpose of learning factories is to modernise and provide a multidisciplinary learning and training environment for both industry and academia that closely resembles reality. This evolvement is partially to respond to the demand for action- and experience-based skill development models and innovations in the field of manufacturing. As manufacturing environments are becoming more and more advanced, it requires workers and engineers to keep continuously learning new thing. Most of the current learning factories are furnished with cutting-edge equipment. Each learning factory is focused on specific issues in regional industries while taking into consideration their expertise and realising university curriculums. [11, 52, 53]

There exist social and technological barriers connected to the industrial implementation of new technologies. Learning factories allow early contact with new technologies, which is an excellent way to overcome those barriers. It aids in minimising the possible fears of workers and managers, related for example, to unidentified changes in the work environment. Learning factories also provide ways to research and test out new technologies before fully implementing them to industry. [51]

2.3.1. Mixed Reality in Learning Factories

Learning factories places for education, research and training in industrial and factory-related subjects. In learning factories, physical and virtual elements can be combined for a practical learning experience. The connection to hardware adds a tangible element to the learning experience. Virtual elements, alternatively, provide learners with experience in methods, processes and scenarios that are not obtainable in hardware. [45]

Mixed reality technologies allow the development of user interfaces in which physical and digital objects can be connected and combined. Mixed reality applications are becoming more and more utilised various areas, for instance, health care, engineering, manufacturing industry, architecture and construction, but also education. In educational environments, the central potential of mixed reality is to combine physical, digital and social learning experiences in hybrid learning environments. Studies have shown that learning in such environments often results in learning benefits, greater motivation or increased interaction and collaboration in contrast to other entirely physical or entirely virtual learning environments. [54]

Learning factories enhanced with mixed reality have the potential to act as excellent hybrid learning environments [11] both to learn about capabilities and applications of mixed reality and to work with them in manufacturing settings and to learn with mixed reality about processes and relations in the industrial context. Simultaneously, learning factories, serve as a vast field of application for the most diverse forms of mixed reality along the reality-virtuality-continuum. [54]

Mixed reality allows learners to assume responsibility for their training and learning speed. It can also be used to motivate learners in specific topics. Mixed reality can also enhance the efficiency of education and training by supplying the learners with the right information at the right time and space. This more tangible form of education is especially important when learning about complex and perhaps yet abstract topics such as the digitalisation of manufacturing processes and industry 4.0. [45]

Mixing digital content with the physical world aids in the understanding of processes, systems, data and systems. Additionally, the users can experience learning scenarios that would otherwise be too complex, expensive or dangerous to execute only in the physical world. Mixed reality can broaden the functional, spatial and temporal scope of a physical learning factory. In a learning factory, mixed reality makes it possible to visualise digital data and put it into spatial context with real machines, production systems, processes and products. Thus, data, information, states and indications for fields of action can be visualised and augmented. These capabilities can show learners instructions in new ways and more effectively imparting knowledge and skills. If mixed reality can be enhanced with not just visual elements but also sound or other sources of natural user interfaces, it becomes more instructive. Moreover, by augmenting digital process information into real machines or making usually unseen information visible, a higher level of transparency can be reached in a learning factory. [41, 45]

In mixed reality learning environments, real-time feedback on practical actions is essential. The inherent capability of such data-related interactivity is based in that it supports learners in the process of forming a coherent mental picture of the system being studied. Data-driven mixed reality allows creating and directly verify multiple micro-hypotheses such as qualitative correlations between experimental parameters and both system and model behaviour. Data-driven mixed reality can be used to build hybrid environments that closely connect objects, data and actions of the physical world with elements of the virtual world. Learning factories are an excellent example of learning in and about complex systems. A possible challenge for implementing such a mixed reality system in learning factories originates from integrating it for the whole process chain instead of single subsystems only. [45]

As mixed reality can expand the spatial perspective, it can also break up the physical limitations of a learning factory. Thus, global relationships, such as environmental impacts or material flows, can be immersively practised. The physical infrastructure of a learning factory can also be virtually broadened. For example, machines can be augmented with virtual parts indicating various configurations while not having to spend money on the actual hardware and set-up times. Similarly, product options and modifications can be simulated without needing to acquire them physically. With the help of mixed reality emergencies or process break downs can be experienced and trained for appropriately in a safe environment. [45]

The spreading of new technologies and concepts such as mixed reality and industry 4.0 is often hindered because their potential needs to be understood before they can be effectively applied to practice. Learning factories offer a great environment to learn about the capabilities of mixed reality within an industrial context as well as to use mixed reality to learn more effectively about work, tools, hardware and software in intelligent manufacturing environments. [45, 54]

2.4. Strategic Management of Information Systems and Technology Implementations

2.4.1. Issues Hindering the Implementation of the Industry 4.0 Paradigm

Manufacturers are becoming more and more aware of the benefits that cyber-physical production systems and other industry 4.0 technologies can provide. Still, most manufacturing companies are not taking advantage of these technologies but operate with unconnected resources and without taking the full advantage of the available data. Research implies that this fact is a result of manufacturers often being risk-averse, unwilling to make substantial investments to new technologies. Also, not enough research exists to provide the manufacturers with sufficient understanding of the industry 4.0 paradigm to help them make the needed leap. [21, 38]

For smart manufacturing systems to become fully implemented within the field of manufacturing, they need to be integrated through the whole supply chain as well as through assets within the companies themselves. This integration requires that cyber-physical production systems become robust, resilient and cost-efficient. For the manufacturing industry to adopt the paradigm of Industry 4.0, cyber-physical systems need to be quick to deploy with an attractive return of investments, as well as providing transparent communication of functionality to end-users. [38]

Difficulties in the standardisation of Industry 4.0 concepts slows down the implementation of flexible and adaptable systems. Manufacturing assets are not yet as well connected as the existing technologies would suggest, and those who are, tend to be very customised, instead of following standardised or unified protocols. [14, 20, 23] This leads to end-users having to solve the challenge of seamlessly connecting the different aspects of smart manufacturing processes. Such situations leave end-users faced with challenges to bring seamless connectivity into their manufacturing plants. However, there are several developing initiatives in an attempt to standardise the field and to make technologies involved in it more openly accessible. [20] One of the most well-known attempts to create some standards in the field of Industry 4.0 is the Reference Architecture Model Industrie 4.0. Its goal is to establish a standard for the connection of elements in the physical and virtual world. [23, 26].

If a manufacturing enterprise can combine the operations of its production facilities in a way that all available information affecting them can be utilised, then significant economic returns will be achieved. This idea is very tempting, and thus many organisations are attempting to make it a reality. However, such attempts can fail quickly if the organisation in question does not diligently take care of the fundamental requirements needed for the successful implementation. [55]

The first reason why such an attempt may fail is due to biting off more than they can chew in one go. Manufacturing digitalisation projects are usually large, and if a company tries to execute it as one enormous project, it will most likely be beyond the resource capabilities of even the largest companies. Simultaneously, there are few successful examples of how to break these large projects into appropriate sub-units. [55]

The second main reason for failure results from approaching the problem in a fragmentary, disorganised or bottom-up manner. This approach often leads to “islands of automation”, or several small projects that cannot be joint together when each of them is finished. This undesired result is due to the lack of one, single communications and interface discipline, that was not known or enforced during their development. Consequently, it is impossible to achieve an overall integration with the resulting optimality. [55]

Thirdly, even if the system succeeds technologically, it may fail because operational and administrative staffs do not accept it. This personnel may feel a lack of ownership of the changes, which can be a result of upper management not involving them enough in new developments. It can also be a result of an employee’s fears of competence or job security concerning the new system. [55]

An essential factor in implementing new technologies is a company’s wish to gain a competitive edge [33]. However, the implementation of a new production system can fail to produce the intended change, despite this. This failure can result from the incapability of an organisation to implement the underlying strategic purposes of implemented, already existing information technology capabilities. [56] However, it is important to note, that highly optimised technical infrastructures that provide exceptional performance at low cost may end up as too rigid if they are required to uphold swiftly changing and highly agile business processes. [57]

2.4.2. Strategic Management of Information Systems and Technology Implementations

These days and even more so in the predicted era of the industry 4.0 paradigm, most organisations in all industrial sectors, as well as government and commerce, rely critically on their information systems. These systems should be advanced: they should have the ability to identify the most advantageous combination of information systems and technology investments to make to support business objectives utilise new information technology options possible. However, developing such an information systems strategy is becoming more demanding as the applications involved are becoming both more complex and more strategic. Furthermore, it demands the innovative use of information technology and systems and the ability to make more dramatic but sustainable business changes to gain more profits. Additionally, if these systems dysfunctioned dramatically, the organisations involved would lose a significant part of their businesses [58]

According to Arvidsson et al. (2014), it is important to understand strategy implementation as *"an embedded process that actors make sense of, respond to and actively shape based on the practices to which they belong"*. This understanding is especially crucial in the case of implementing Industry 4.0 strategies, as smart manufacturing processes can easily complicate the strategic role of Information Technologies. Whether or not the implementation is a success depends on how well the implemented systems become embedded in new organizational practice and routines, that way becoming accepted by the users. In addition to this, Arvidsson et al. press, that the implementation of new technologies and strategies is successful when a system is implemented on time, at a reasonable cost and with acceptable risk. [56]

Looking from the other side of the coin, proper information technology and systems infrastructure can supply an organisation with cost savings and access to expertise, further advancing the economic value of the company. The organisation in question should be able to yield definite business value from information systems investments continuously, to make such a system sustainable. It is this ability that makes an organisation enduring, not some specific technology like a magic wand or silver bullet. This capability is crucial for organisations, but its development is anything but straightforward. Achieving information systems sustainability demands an understanding of different aspects of the system as well as what contributes towards the formation of those aspects. [58]

For-profit organisations, naturally, care about their bottom line and thus are continually searching for ways to increase their competitive advantage by using and combining old technologies in new ways as well as searching for new ones. Superficially, it is easy to assume that adopting a new technology application may give a company a direct advantage. However, the technology can be speedily replicated by competitors, thus making the perceived advantage unsustainable. Therefore, to gain a real competitive edge through the formation of information systems and technology, it is vital to comprehend the mechanisms and processes that lead to circumstances where an organisation repeatedly and continually carries out financially beneficial outcomes. Which is especially crucial as investments made in technology infrastructure are becoming more and more essential. Making the wrong decisions related to this domain can damage an organisation's agility, which in turn can hinder the competitiveness of the organisation. In this context, agility means the competence to react to altering market conditions quickly. [58]

Resources as such do not generate value; value is built by an organisation’s capability and competence to utilise and organise the resources at their disposal and to combine those resources to affect a wanted outcome. Technology, be it hardware or software-based, by itself does not have any ingrained value and information technology, and systems do not single-handedly provide a sustainable competitive edge. The financial benefits an organisation obtains through investment in information technology only materialise through business alterations and innovations. These can involve product and service innovations, new business models, or process changes. For all of this to be successful and value to be tangibly achieved, organisations must be capable of adapting and adjusting to these changes. [58]

Truly benefiting from all that technology offers, demands that an organisation understands how systems and information boost its operations presently and optimally, which demands continuous investments in developing competencies that, once matured, allow the organisation to utilise the technology, systems and information it has. Also, with the gained knowledge, the organisation can make further investments that deliver specific and unambiguous, measurable value through achieved organisational performance improvements. An organisation may not manage to steadily achieve these factors unless it already has developed a full set of information systems competencies through a history of successful implementation of new technologies and business strategies. To have achieved this, in turn, implies, that the organisation already has focused on the ways it manages and uses information systems and technology. In such a case the organisation would have had to learn from its successes and failures, instead of only concentrating on what technology can do, or trying to align information systems and technology used to carry out set business objectives. Thus, such an approach often sets the investments in jeopardy and changes the agenda whimsically and by chance. [58]

According to Peppard and Ward (2004), the achievement of sustained information systems founded on competitive advantage may be the result of creating an ‘organizational infrastructure’ to allow innovative and adaptive action strategies. [58] This method is often called enterprise architecture.

Information technology has the power to disrupt any industrial enterprise, so it must be incorporated into any strategy development. All information technology-related investments should be adequately planned for and coordinated to corporate strategy. Approaches, frameworks and models have been developed to successfully integrate different success factors and aspects and the process of information systems and technology strategy evolvement. Alterations in a company’s business goals and strategy substantially affect all domains of the organisation, including organisational structures, business processes, technical infrastructures, software systems and data management, among other things. Companies must accommodate processes to their environment, expose internal systems and make them transparent to both internal and external stakeholders. [59]

2.5. Enterprise Architecture and Modelling – Background for the Methodology

Surviving in a continually changing environment requires organisations to be able to adapt and change regularly. To be able to do this, the organisations should be agile and able to evolve compactly, characteristics supported by technology and business strategies. [60] To achieve agility and flexibility, the organisation needs to understand and handle the complexity of any large organisation or system. A unified view of a system being studied or designed is needed. This unified view is achieved by deploying sufficient architectures or “structures with a vision”. [59]

Enterprise architecture refers to the architecture of a whole organisation [59]. The concept of enterprise architecture was developed in the late 1980s [61] to deal with systems complexity [62] and the poor alignment between business and technology systems. These two issues hinder the view of an organisation holistically, as well as need steady attention. Thus, enterprise architecture acts as the organising logic for business processes and information technology infrastructure that reflects the integration and standardisation of the company’s requirements. [60]

The goal of enterprise architecture is to generate documentation, which both functions as a plan for an organisation's ongoing future information technology environment, and supplies the management guideline to move from a present to a future state [63]. Enterprise architecture details the present and beneficial future states of an organisation’s capabilities, processes, IT infrastructure, and application systems, as well as data and data flows. It also equips the organisation with a guide for achieving this desired future state from the already existing state. These entities are detailed using an array of standardised representation techniques. [12] Enterprise architecture facilitates the alignment of an organisation’s business strategy with its information technology strategy and performs a decisive role in the planning of business and information systems, especially in large and global organisations. [12, 60] Enterprise architecture can also be defined as a way to manage and organise business processes to allow information technology infrastructure to unify and standardise the management of the enterprise as an operational model [61].

Organisational agility is the ability to race in new directions as needed without breaching the core infrastructure and without putting the organisation at unnecessary risk. Organisational agility has four perspectives: cost, time, quality and scope. For an organisation to be truly agile, it should achieve all these dimensions should. Literature often points out organisational agility as one of the main benefits of enterprise architecture. However, few empirical studies have supplied enough support the claim. There is some controversy on how exactly enterprise architecture helps to make an organisation more agile. Multiple research papers suggest organisational agility to be a direct or indirect advantage of enterprise architecture. Other studies regard organisational agility as a result of organisational alignment, which results from the deployment of enterprise architecture. [60, 63]

When planning to develop and change some things in an organisation, it is vital to be able to predict what impacts such modifications have on the organisation's information technology and business actions. For the predictions to be accurate, an overview of the developments and their effect on each other is needed. Also, both people making decisions and people implementing the changes need necessary information for their jobs. [57]

Enterprise architecture presents the crucial and fundamental aspects of the business, information technology and their evolution. These fundamentals are usually considerably more constant and stable than the individual solutions established for the current problems in the organisation. Along these lines, enterprise architecture helps in preserving the fundamentals of the organisation, while simultaneously granting flexibility. [57]

However, it is important to note, that even though an enterprise architecture presents the moderately constant parts of business and technology, all architecture must become suitable for change and facilitate it. Architectures change because new technologies are developed, and the environment changes. Besides, perceptions of what is essential to the business can also change. Also, after an architecture has been created, it requires regular maintenance. Businesses and information technologies are always changing. [57] Architecture within an enterprise is likely to change over time. It is crucial to be able to analyse the consequences of these changes when planning future developments within the enterprise. In an ideal situation, an enterprise architect can create a big picture of different domains and stakeholders. [59] Reaching alignment between business and information systems is a constant process because it is affected by the organisation's business strategy, continuous technological improvements and market circumstances [61].

Enterprise architecture grants a holistic view of an enterprise. Thus, a good enterprise architecture gives an organisation the insight required to balance the more specifics needs of different local domains within the organisation while assisting the progress of the translation from corporate strategy to daily operations. Creating a holistic view of an organisation and creating a big picture putting different domains together demands an integrated set of methods and techniques for the analysis, communication and specification of enterprise architectures that answers to the needs of the diverse types of stakeholders involved. [57]

Well-developed enterprise architecture can create insights and overview in order to translate strategy into execution. It allows senior management to make well-informed decisions on the design of the future enterprise. These decisions can, for example, be information technology investment decisions. Enterprise architecture helps to guide and inform these decisions. Thus, enterprise architecture helps to increase these decision qualities. [62]

As described, there are many benefits of enterprise architecture and the vast amount of studies centred around the topic [60]. Despite this, many organisations regard enterprise architecture as an abstract concept that involves considerable investments but only vague benefits or ambiguous value generation. One of the reasons for these perceptions is that the rewards associated with enterprise architecture may take years to surface. [12]

Enterprise architecture and modelling are compelling approaches for the analysis of the system integration concerns of information and communication technology systems, especially in an era where automation systems are becoming more and more involved with evolving technology [64].

Successfully combining and organising information from different domains requires an approach that is understood by all those involved from these different domains. Unlike in building architecture, business and information technology worlds have no commonly established and adopted language and culture, nor thus a proper frame of reference. Currently, architecture descriptions are heterogeneous; each domain has its description methods. Communication and decision making between different fields are severely flawed. However, it is up to the organisation in question to decide what it defines as part of enterprise architecture and what is simply an implementation within that architecture. [57]

Well-determined enterprise architecture is essential when fitting new things inside the context of already existing processes, information technology systems and other organisational aspects. It also aids in determining the required changes in an organisation. Hence a robust architectural practice assists organisations innovate and change by supplying both stability and flexibility.

Enterprise architecture provides insight that the organisation needs to determine the requirements and priorities for change from a business perspective as well as to estimate how the organisation can profit from technological innovations. [59]

According to Rouhani et al. (2015), the usefulness of an enterprise architecture practice is measured by how well its outputs can aid an organisation to reach its goals. The usefulness of an architecture can be objectively assessed by, for example, utilising organisational performance data connected to the implementation of enterprise architecture related decision-making. [65] Besides, according to Jonkers et al. (2006), the value of enterprise architecture depends on how well it benefits the different stakeholders of an organisation. These stakeholders can include anyone from managers to developers and designers. For the stakeholders to be able to benefit from enterprise architecture fully, they need appropriate tools and instruments. [59] Many organisations have trouble with the implementation of enterprise architecture. Studies suggest that failure to implement enterprise architecture properly is caused because the organisations begin the implementation process with modelling instead of first distinguishing business, information technology, information systems and management needs. [61]

2.5.1. Stakeholder Roles in Enterprise Architecture

In any company or organisation, multiple different stakeholders can be identified both within and outside the organisation in question. These stakeholders can range from top-level management to machine operators and software engineers. Each stakeholder needs detailed information presented in an accessible manner, to help them handle different aspects of their jobs as well as to cope with possible new developments and their impact. [57, 59] Enterprise architecture supplies organisations with a method to cope with the complexity of modern information-intensive enterprises. It should communicate the architecture with clarity and be understandable to each stakeholder. [57]

The process of creating an enterprise architecture also raises different stakeholders' awareness of business objectives and information flow. It is essential to understand, that majority of the stakeholders of any organisation will most likely not be interested in the architecture itself, but only the effect it has on their interests. Thus, it is vital for the person designing the architecture, the enterprise architect, to be conscious of the interests and concerns of the stakeholders and discuss them with the stakeholders. It is equally essential to be able to clarify the architecture to all stakeholders involved. [59]

Besides, different stakeholders often have entirely different backgrounds. Thus, enterprise architecture plays a crucial role as a communication tool among different groups and interests and provides a point of mutual understanding for discussion and decision making. [59] It can often be useful to integrate the stakeholders as a part of the enterprise model design [61].

All organisations profit from explicitly understanding their structure, technology, operations, products and the network of relations tying these together and connecting the organisation to the outside world. These outside factors include, among others, suppliers, customers, and other business partners, as well as regulatory bodies. Taking outside factors into consideration is especially important in the modern world, where everything is becoming more and more networked, and no organisation can focus only on their operations, completely disregarding the outside world. Thus, enterprise architecture is a useful tool in the understanding of interconnections with suppliers, customers, and other partners. [57, 59]

In addition to the organisation's internal desire to efficiently implement an organisation's strategy and optimise its operations, also external factors can urge organisations to adopt enterprise architecture practices. These factors can include, for example, laws and regulation which demand that companies and governmental institutions prove that they comprehend their operations and that they abide by the laws concerning their activities. [57, 59]

The enterprise architecture defines the line between the essentials, that should not be meddled with and the things that can be filled in more freely. Consequently, the requirements for quality architecture are high. A high-quality architecture aids an organisation to achieve its essential objectives. Therefore, the choices made when building and maintaining an enterprise architecture should be related to the goals of the organisation. Consequently, enterprise architecture can also be examined from the viewpoint of quality management and ISO 9001 standard. Thus, enterprise architecture primarily contributes to the integrated design, management and documentation of business processes, and their supporting information technology systems. A well-designed and documented enterprise architecture aids organisation in following the ISO 9001 requirements on process identification and documentation. [57]

2.5.2. Enterprise Architecture Frameworks

The most famous tool for creating enterprise architectures are different enterprise architecture frameworks [61]. The purpose of enterprise architecture frameworks is to structure architecture description techniques by identifying and linking different architectural perspectives and the modelling techniques connected to them. Frameworks do not offer approaches for the modelling itself, even if some frameworks are associated with a particular modelling language or set of languages. Most architecture frameworks are relatively specific in defining the elements that should be part of an enterprise architecture. However, the implementation of a framework is not sufficient to guarantee the value of the enterprise architecture during its life cycle. The connections between the various domains, views or layers of the architecture must remain clear, and all changes should be meticulously executed in all of them. [57]

Examples of different architectural frameworks include the Zachman Framework, Purdue Enterprise Reference Architecture (PERA), Federal Enterprise Architecture Framework (FEAF) and the Open Group Architecture Framework (TOGAF), among others [64]. The goal of these architecture frameworks is to provide high-level instruction in determining which parts of business and technology should be taken into consideration when designing an enterprise architecture. However, they do not offer much guidance in creating the architectural artefacts themselves. Besides, the problem with most enterprise architecture guidelines is their generic nature. Many of them lack the detail to be invaluable in the creation of enterprise architectures for complex systems. [59]

2.5.3. Enterprise Modelling

Enterprise modelling is the abstract definition, description and representation of the structures, resources, processes and information of an organisation. Where enterprise architecture is mainly used to outline vital concepts as well as recognise views and their relationships to an organisation, enterprise modelling uses semantics or diagrams to provide a clear representation of different views on an organisation. Enterprise modelling methods allow the understanding of the behaviour, structure and performance facets of an organisation, and they can also be categorised into views of enterprise architectures. Numerous enterprise modelling methods and languages have been developed by the industry and academia to deal with the increasing complexity of organisations. Examples of enterprise modelling languages include UML (unified modelling language), DFD (data flow diagram), ERD (entity relationship diagram), EPC (event process chain), BPMN (business process modelling notation) and ArchiMate modelling language. [57, 64]

One of the challenges in the field of enterprise architecture is the vast amount of modelling languages [63]. None of the languages has accomplished in becoming a language that can cover all domains, whether from a technology, application or business perspective. In most enterprise modelling languages, the connections between domains, or views, are poorly defined, and the models created in different views cannot be adequately integrated. Enterprise architecture is often regarded to consist of four architectural levels: business level, applications level and technology level. [60] Thus, most languages fail in achieving a general architectural vision and are restricted to either the business or the application and technology subdomains, not being able to cover all three. Furthermore, most modelling languages have a deficient formal basis and miss a clearly defined semantics, or they are challenging to understand by all the stakeholders. [57]

International standards have been developed and published to establish a way to identify the requirements for enterprise models, the creation of enterprise modelling frameworks and the development of enterprise modelling methodology, respectively. These international standards include, for example, ISO 15704, 19439 and 19440. According to the United States National Institute of Standards and Technology, these three standards are the foundational elements of its suggested smart manufacturing eco-system. This point of view implies that these standards in question are paramount in identifying smart-manufacturing-related standards. However, these standards are over a decade old, which raises the question of whether they are up to the task, as Li et al. (2018) point out in their study. Indeed, Li et al. (2018) suggest that the standards in question should be revised due to the new developments in enterprise architecture and modelling as well as emerging technologies, such as cloud computing, internet of things and cyber-physical systems. These emerging technologies present considerable challenges to enterprise infrastructure and operation. [64]

Already, enterprise architectures are used to deal with systems engineering issues of complex information and communication technology-based industrial systems. Following the industry 4.0 related technological advances within the global industries, many organisations have built domain-specified architectures to understand enterprise integration better and in a more holistic manner. Examples of these kinds of architectures are the Reference Architecture Model for Industry 4.0 [23] and the Industrial Internet Reference Model by the Industrial Internet Consortium [66]. Frameworks for the internet of things and cyber-physical systems have also been developed. [64]

3. Methodology

3.1. The Learning Factory at NTNU Gjøvik

The learning factory situated at NTNU Gjøvik is provided by Festo Didactic and classified as a cyber-physical learning factory. The cyber-physical learning factory is designed for teaching and research purposes. It can be used not only to demonstrate an assembly line but also various areas of production, for example, lean production, logistics and quality assurance. The learning factory contains the essential elements and technologies required for imparting a comprehensive understanding of industry 4.0. Its flexible and modular nature enables a variety of learning scenarios, from individual pallet transfer systems with an integrated controller to a connected production system with cloud services. [67]

The central element of the learning factory is the collection of flexibly combinable modular stations, which are used to realise various application modules. The different application modules determine the learning content supplied by the stations. The application module can be practically anything from an inspection camera to a muscle press or a robot. All the stations and modules are equipped with standard interfaces. Even though the application modules vary from each other depending on their functions and capabilities, base modules are built identically with the same dimensions, control cabinet, conveyor belt, control console, track rollers and system cables. Thus, the system can be quite easily altered for different training situations, scenarios and content. [67]

The cyber-physical learning factory is a model of a smart production facility, where physical and computing processes are interlinked and mutually dependant. In an industry 4.0 factory, intelligent machines and workpieces communicate with each other and with the information technology system. The information technology system encompasses an enterprise resource planning and manufacturing execution system, which run both inside and outside the physical boundaries of the learning factory, up to cloud level. Festo's software for manufacturing execution system is MES4, and it is based on an Access database. [67]

The system is highly modular, which allows the addition of new modules as well as changing the layout or order of the modules. Each module is individual, only communicating with the manufacturing execution system, not with each other. The manufacturing execution system is connected to all the modules and knows what is happening with all of them. One module does not know what is going on with the other modules. [67]

Each modular cell, or station, consists of a base module and an application module, pictured in Figure 2. A conveyor belt is positioned between the base modules and the application modules. The workpieces are positioned on carriers equipped with RFID-chips and move through the system on the conveyor belt. Other modes of transport in the learning factory is the mobile robot which transports storage boxes with workpieces to where they are needed. [67] The more detailed structure of the learning factory is presented in the results section of this work.

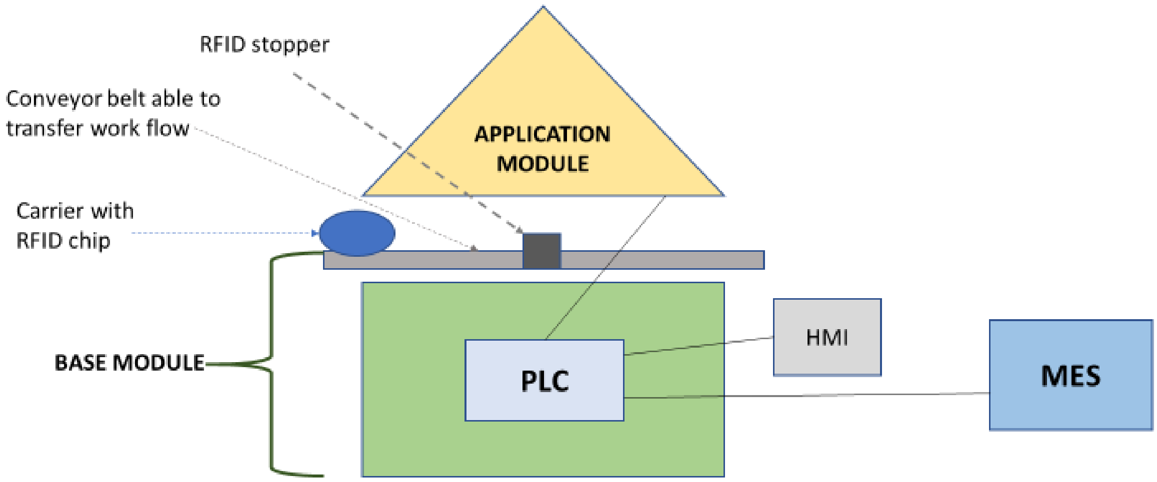

Figure 2. Structure of a CP learning factory module. Each station consists of a base module and an application module. The station is controlled through the MES that communicates with the PLC in the base module. Users can also interact with the station through the human-machine interface (HMI)

The cyber-physical learning factory at NTNU Gjøvik is a part of the interdisciplinary MANULAB infrastructure, a Norwegian research infrastructure for cutting-edge manufacturing research. With laboratories located at Gjøvik, Raufoss, Trondheim and Ålesund, the MANULAB infrastructure consists of front-line facilities and scientific equipment as well as a shared scientific database and e-infrastructure. The MANULAB facilities are accessible to all researchers and industry in Norway, within the boundaries of state funding and ESA regulations. [68, 69] However, the other entities of the MANULAB infrastructure in more detail are outside the scope of this study.

3.1.1. Mixed Reality Properties of the Learning Factory at NTNU Gjøvik

There are some existing default settings for the use of augmented reality in the cyber-physical learning factory at NTNU Gjøvik. These are pre-set properties designed by Festo Didactic that have not been modified yet. However, the augmented reality properties are currently focused on only two stations and are not very intuitive, user-friendly or practical. It is possible to expand the augmented reality functions to all the stations of the learning factory if necessary.

The augmented reality properties are used through the Festo Didactic augmented reality mobile application [70] and a plug-in symbol (pictured in Figure 3) on the stations. Currently, the augmented reality properties are functional on two stations, and the functions are identical on both. However, it is possible to develop more scenarios according to the university's and MANULAB's requirements and integrate them into the application by Festo Didactic. The predetermined augmented reality functions include:

- the ability to open Festo's info page about the station
- showing a video simulation about the station at work
- technical specifications
- Festo's complete user manual in PDF-form
- circuit diagrams
- a generic link to an info page about the augmented reality properties by Festo
- information about different components of the station

Figure 3. Camera station and the black and white augmented reality plug-in (on the left). The same station through the view of the Festo AR app (on the right).

3.2. Literature Search

Literature used in this study was gathered via the internet from different databases for scientific publications, such as ScienceDirect [71] and SpringerLink [72]. This choice was made to limit the result of the search and most of the sources to scientific publications. Different keyword combinations were used, including, but not limited to "industry 4.0", "augmented reality", "mixed reality", "virtual reality", "cyber-physical systems" and "enterprise modelling", "learning factories". Besides journal publications, several books, reports and other web sources were used.

A large part of this study was based purely on literature sources. Thus, it was essential to verify the quality of the data gathered to ensure the truthfulness and accuracy of the work. The quality of the journal publications was verified by using the Norwegian Register of Scientific Journals, Series and Publishers by the Norwegian Centre for Research Data [73]. It is a database containing information on approved scientific journals, series and publishers, from Norway and world-wide. The reports and web sides used were by well-known and trustworthy organisations and entities.

3.3. Surveys and Interviews

Interviews and questionnaires were used to gather information and viewpoints concerning data needs and mixed reality from different stakeholders involved with the cyber-physical learning factory at NTNU Gjøvik. As the resources to perform this study were limited, the scope of the study was limited to involve four stakeholder groups: these included lab personnel, students, teaching staff and researchers. In a university setting, however, these roles naturally overlap in some cases.

Two written questionnaires were created: one for students and the other for staff. This divide was made to make the data gathering and participation by the stakeholders easier. A written questionnaire form was chosen due to accessibility, resources and time limitations. Such a survey is easy to share as a link and participation is straight forward. The questionnaire for students was shared on Facebook [74], and the one for staff was shared on a Microsoft Teams

[75] platform dedicated for the learning factory. Thus, the appropriate candidates for each survey were easier to find.

The questionnaires were created using the Typeform [76] platform, as it was experienced to be more user friendly by the author of this work than, for example, the Google forms [77] platform. It is also an anonymous platform, so specific answers cannot be linked for individual participants. The interviews were performed face-to-face or via the Zoom [78] video conferencing platform. Both open and closed questions were used in all cases.

The data gathered from the questionnaires and interviews were used as input to an enterprise model that will be presented later in this work. The questions presented for the students are presented in Appendix A, Table 1. The questions for staff can be found in Appendix B, Table 2. The latter were also questions presented in the interviews, even though the interviews were performed more like conversations.

3.4. Enterprise Modelling

Part of the goal of this study was to attempt to model the main elements of the learning factory, potential use of mixed reality in it as well as different data views for different stakeholders. The modelling was performed by focusing on the capabilities of the cyber-physical learning factory, not on specific technologies or service providers as this makes an enterprise more agile and flexible. Three different models were created: a model for the entire learning factory, a model for its information technology infrastructure and finally, a model for the communication between different stakeholders and machines using mixed reality platforms. Different data views for different stakeholders were also considered.

It should be noted that the models presented only describe a part of the reality of the learning factory. The rest of the aspects are outside of the scope of this study. Besides, a model is a simplified depiction of the real world, or it is part or phenomenon. In a model, the essential parts and relations of the represented phenomena are accentuated [59]. Thus, the reader should be aware that not every single detailed can be modelled.

Even though UML is the commonly used modelling language in the field of information and communication technology, this study uses the ArchiMate 3.1 Enterprise Architecture modelling language, by The Open Group. This language was chosen for various reasons. First, the author of this work is relatively new to the field of enterprise architecture and because ArchiMate is less complicated than UML. Also, UML is not effortlessly available nor understandable for managers or other stakeholder groups not involved in enterprise architecture. [57, 79] Unlike UML, ArchiMate has been developed to model the dependencies and relationships across all viewpoints of an enterprise architecture. These viewpoints include technology, applications and business layers, thus giving a more comprehensive view of the whole organisation. [80] This is especially important with increasingly complex systems, such as industry 4.0 environments.

The ArchiMate language lines up closely with the TOGAF framework, a standard of The Open Group as well. Also, both ArchiMate language and the TOGAF framework are compatible with ISA-95, the International Standard for the Integration of Enterprise and Control Systems, by the International Society for Automation. It is a standard for integrating systems used in manufacturing companies, and it directs the exchange of information between enterprise systems for production, maintenance, and quality. ArchiMate language has been designed as a general-purpose language for organisations in different fields, and it can be effortlessly adapted to the domain of manufacturing. [81]

There several different software designed for enterprise modelling with ArchiMate, the one used for this study was Archi [82]. It is open-source software, free to download and use, and partly funded by private donations. One of the reasons why this software was chosen was because it is free of charge, and there were not so many resources available for this study. This availability is in alignment with NTNU's policy to prefer open-access documents. Open access increases transparency and accessibility. Enterprise Architect was also considered, but it is a heavy software that has a trial period of only 30 days [83].

4. Results and Analysis

4.1. Main Literature Findings

The literature review has inspected the core components of the industry 4.0. paradigm. It has also discussed mixed reality as an enabling technology for smart factories, them being the only industry 4.0 technology focusing solely on helping humans cope in these new environments. Involving also humans are the learning factories, which focus on training future industry workers in increasingly complex manufacturing systems and act as facilities for research and development. Finally, no organisation can develop their processes without appropriate strategy management capabilities and organisational structures.

4.2. Interview and Questionnaire Findings

It should be noted that only 14 people answered this questionnaire aimed at students. The low number of participants was disappointing, but people cannot be forced to participate, and the author of this study did not have the resource on her disposal to offer opportunities for prizes or other benefits for the participants [84].

Three staff members were interviewed, and three answered the questionnaire. To clarify, these were six different people. More people were approached and asked to participate in both interviews and questionnaire, but the efforts did not result in the desired outcome, for unknown reasons. As a rule, it is often challenging to motivate people to take part in things that do not directly concern their lives [84].

Thus, the gathered data cannot be considered as representative of all the students and staff at NTNU. Indeed, to produce statistically accurate data from smaller populations, the sample sizes should be quite large in comparison. For example, if the researcher is studying a population of fewer than 100 people, all the people included in the population should be surveyed. If the population is less than 500, 50 % of it should be surveyed to produce data with high statistical quality. [84] On the other hand, the data views an individual may require can be very specific and unique depending on the situation. Thus, the results do indicate at least some crucial elements to serve as input to the enterprise model.

4.2.1. Main Findings from the Questionnaire Aimed at Students

As a background question, the participants were asked whether they were familiar with the concept of mixed reality. While not directly affecting the results of this study, it is an interesting aspect to be aware of, as it affects the students' or industrial trainees' ease to adopt mixed reality as a part of their work. The answers were distributed so that 69 % of the participants answered yes, and the remaining 31 % answered no (as presented in Figure 4).

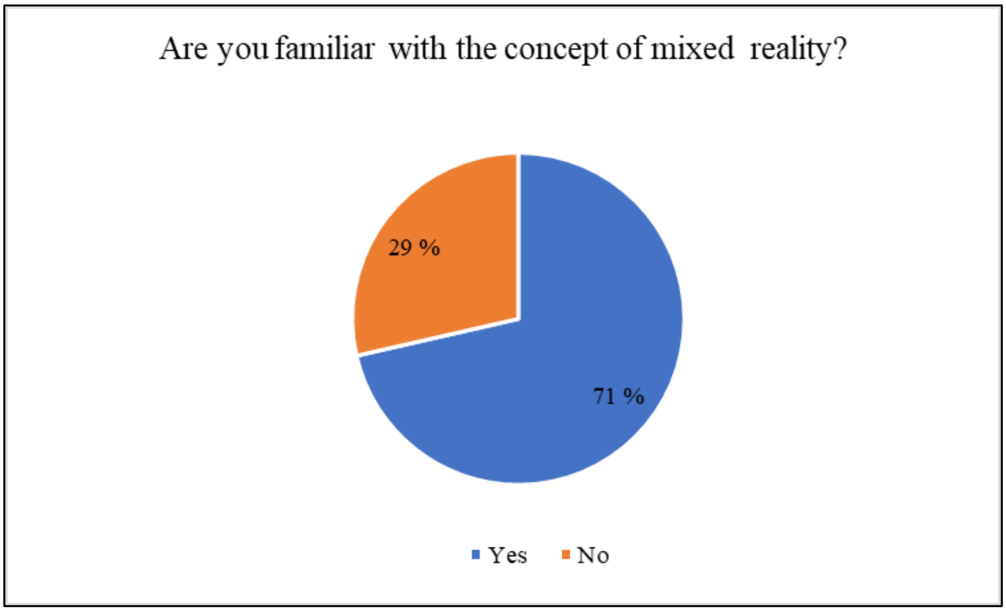

Figure 4 Answers to the question "Are you familiar with the concept of mixed reality?"

Another background question inquired how the participants had become familiar with mixed reality. Most of the participants answered either via studies or games (depicted in Figure 5). This result may give some indication on how to approach the topic with the students using the learning factory, or mixed reality in general, in their studies.

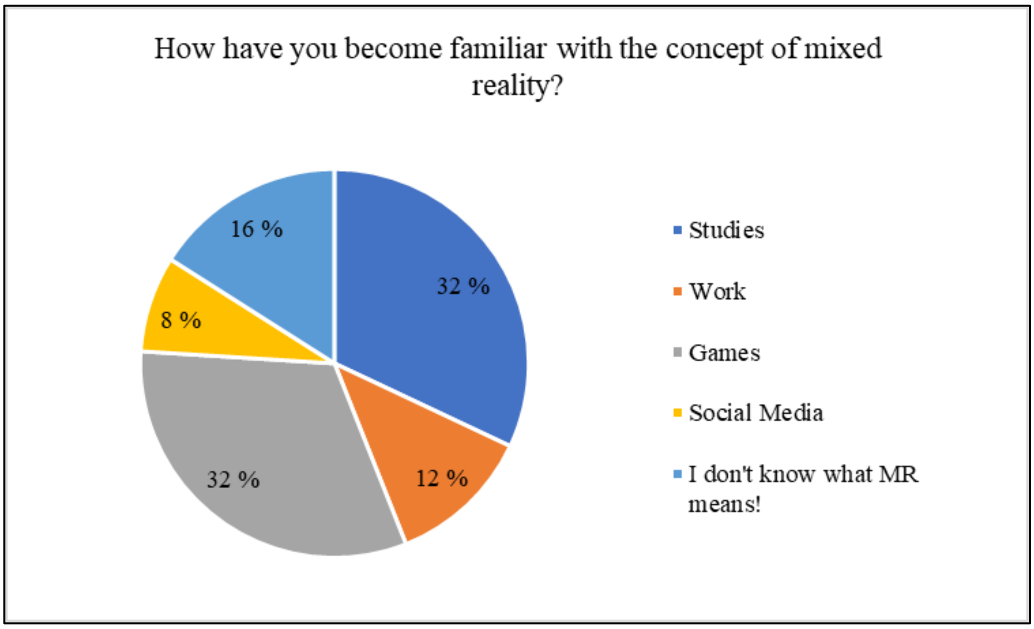

Figure 5 The answers to the question "How have you become familiar with the concept of mixed reality?"

In the question of determining which device functions relating to mixed reality (see Figure 6), the most popular options gathered ten or more votes. These options were the display of safety instructions, advice for fault and error detection, information on a piece of equipment or its part and to help a maintenance professional or service provider to guide the user through a problem. The options chosen for this multiple-choice question were based on literature [9, 10].

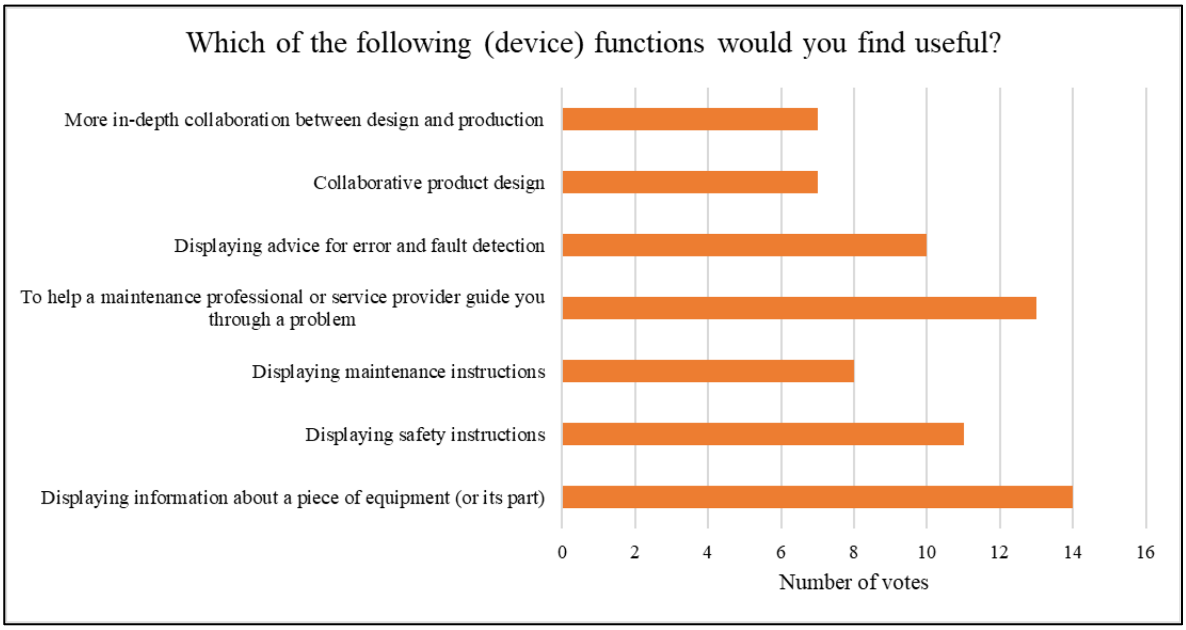

Figure 6 The answers to the question "Which of the following (device) functions would you find useful in a smart factory?"

In an open-answer question asking if the participant could think of any ways mixed reality could help them in their current or future jobs, the answers were miscellaneous. The most common things mentioned were things mentioned in the previous questions as well as general ways to aid in job performance or aid in decision making.

The participants' preferences for mixed reality devices were varied. Most participants thought that type of device should ultimately depend on the situation, but some preferred either wearable devices or handheld ones (pictured in Figure 7).

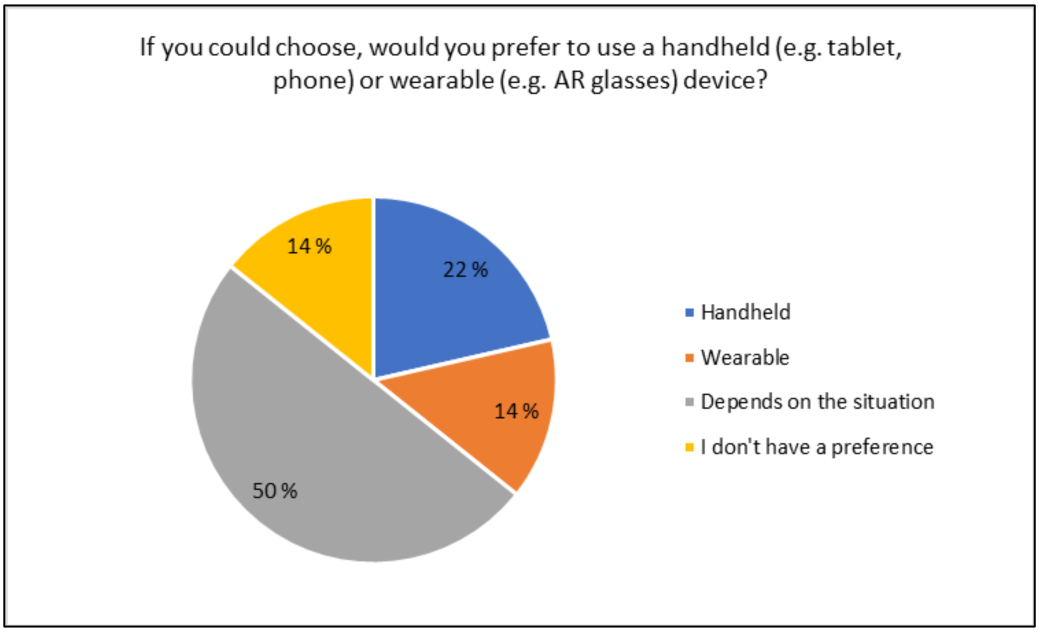

Figure 7 The answers to the question "If you could choose, would you prefer to use a handheld (e.g. tablet, phone) or wearable (e.g. AR glasses) device?"

It should be noted that students from different fields of study, including engineering, design and computer science, answered this questionnaire. The questionnaire was also shared limitlessly, as there is no shared group for NTNU students on Facebook and sharing the results within the sustainable manufacturing study program resulted in just three answers. All in all, this may have led to some participants not being students.

All the data gathered with the questionnaire for students can be found in Table 3, presented in Appendix C, on page 83.

4.2.2. The Interviews and Questionnaire Aimed at Staff at NTNU

In the interviews and questionnaire for the staff, similar questions were asked and discussed. Thus, the results will be presented together. All the answers were very diverse, depending on the person in question and their job description. Especially in university settings, this phenomenon can be quite normal, as different researchers are focusing on different things, even within the same field.

The most meaningful answers have been gathered in Appendix D, Table 4. The gathered data have been sorted out by subject or context, not necessarily by profession or job description, as many of the stakeholders have multiple roles within the university. A person can, for example, participate in both in research and in teaching.

4.3. Modelling Results

As the cyber-physical learning factory and its stakeholders form a complex system, it is better to present the created models in parts here for the sake of reading comfort. This section of the results is approached from the perspectives of different views. The first part focuses on the overall physical aspects of the learning factory. The second part focuses on modelling the information flow between the crucial technological and applicational part of the learning factory. The third part emphases the mixed reality aspect. The final section focuses on the stakeholders of the factory and the data views they may require in their jobs.

The data used to perform and analyse this section was gathered in three ways. First, it was gathered from the surveys explained in the previous section. Secondly, the author's own experiences on working with the cyber-physical learning factory and familiarising herself with its documentation, and partly creating it herself, were used as a basis of the modelling of different structures in the learning factory. Finally, over the past year, the author has had multiple informal but informative conversations relating to it with other people involved with the learning factory.

The legend depicting the different symbols and elements of ArchiMate modelling language can be sound in Appendix E, on page 85.

4.3.1. The Main Physical Structures of the Learning Factory

The learning factory is built of different modular stations. These stations can roughly be separated into mobile and stationary stations. The mobile stations, such as the mobile robot and the mobile workstation, can be easily moved around, either manually or by giving orders via the manufacturing execution system, in the case of the mobile robot. The stationary stations are connected by cables, such as Ethernet and power, but those cables can be detached simply, making the reorganisation of the stations relatively easy. This modularity also allows the addition of new modules to the learning factory if needed. Figure 8 describes the current state of the learning factory. The stations modelled as part of "the solid", or stable, aspect of the learning factory, are connected as one assembly line. The other stations are located separately.

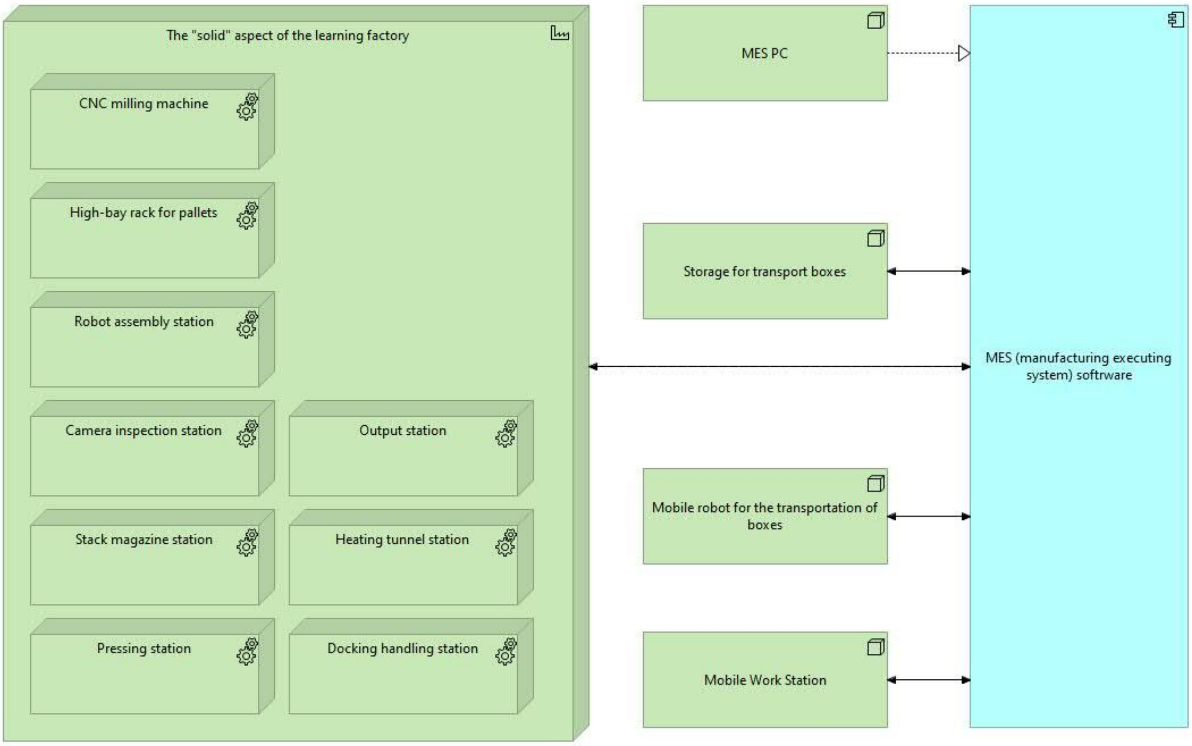

Figure 8 The current main physical components of the learning factory and the flow of information between them and the manufacturing execution system. Even though many of the stations are connected physically, they do not communicate with each other. Each station only communicates with the manufacturing execution system.

4.3.2. The Information Flow between the Core Elements of the Learning Factory

Each station is constructed from a base module and an application module. The basic structures of each station are the same (depicted in Figure 9), as are their communication abilities regardless of the nature of the application module on each station.

Sensors, embedded to the hardware of each station, measure things in the physical world and gather information of the environment, sending the data forward to the programmable logic controller. Actuators execute the changes made by the virtual world, or the manufacturing execution system.

The programmable logic controllers communicate with the sensors and actuators. Programmable logic controllers act in high speed on the factory floor, providing local control and sending orders to the actuators and the application modules. They also communicate with the manufacturing execution system through a TCP/IP protocol. This software allows operators to control everything in the learning factory, including ordering of processes, changing product parameters or determining manufacturing sequences.

The machines do not need to be touched to execute a specific sequence in the factory. If something needs to be changed in the product, the right configuration needs only to be set in the manufacturing execution system. The configurations need to be set in the limits of the properties of the factory and its machinery. Otherwise, a new machine or piece of equipment needs to be added.

It should be noted that the stations do not communicate with each other, only the manufacturing execution system, that gives each station orders. This fact means that depending on the situation; it is not necessary to use all the stations. Thus, the manufacturing execution system only gives orders to the desired stations, while the workpieces just pass the inactive ones on the conveyor belt. However, the base modules of the assembly line part of the learning factory are connected through power, pressure and Ethernet switches.

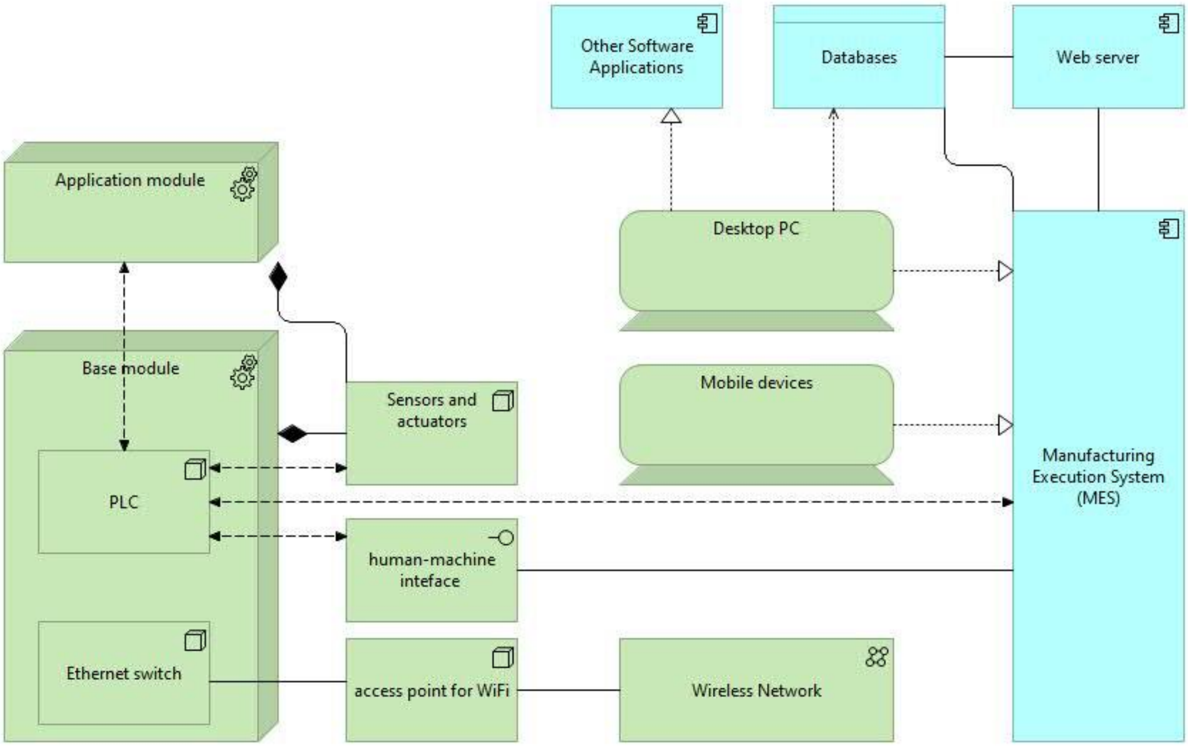

Figure 9 Information flow between the critical elements of the learning factory. One modular station in the learning factory is composed of a base module and an application module. The manufacturing equipment "application module" can be anything from a storage unit to a camera or robot. The structure of each station is the same, regardless of the nature of the application module.

4.3.3. Mixed Reality User Interfacing in the Learning Factory

With the right equipment, mixed reality tools can be used together with nearly every physical aspect of the learning factory. The piece of manufacturing equipment can be nearly anything, and the mixed reality application can cover nearly all physical aspects of the factory. For the sake of clarity, however, only one piece of equipment is pictured in the model presented in Figure 10.

For the mixed reality functions to work, the equipment in the learning factory requires plug-ins. Scanning the plugin through the camera of the mixed reality display device, while the mixed reality application is active, will trigger the mixed reality functions programmed. In theory, the data for this can be unlimited, thus storing the data in the cloud may be prudent. Best would be if the user could log to the interfacing device with unique identification data to get the necessary data designed for them.

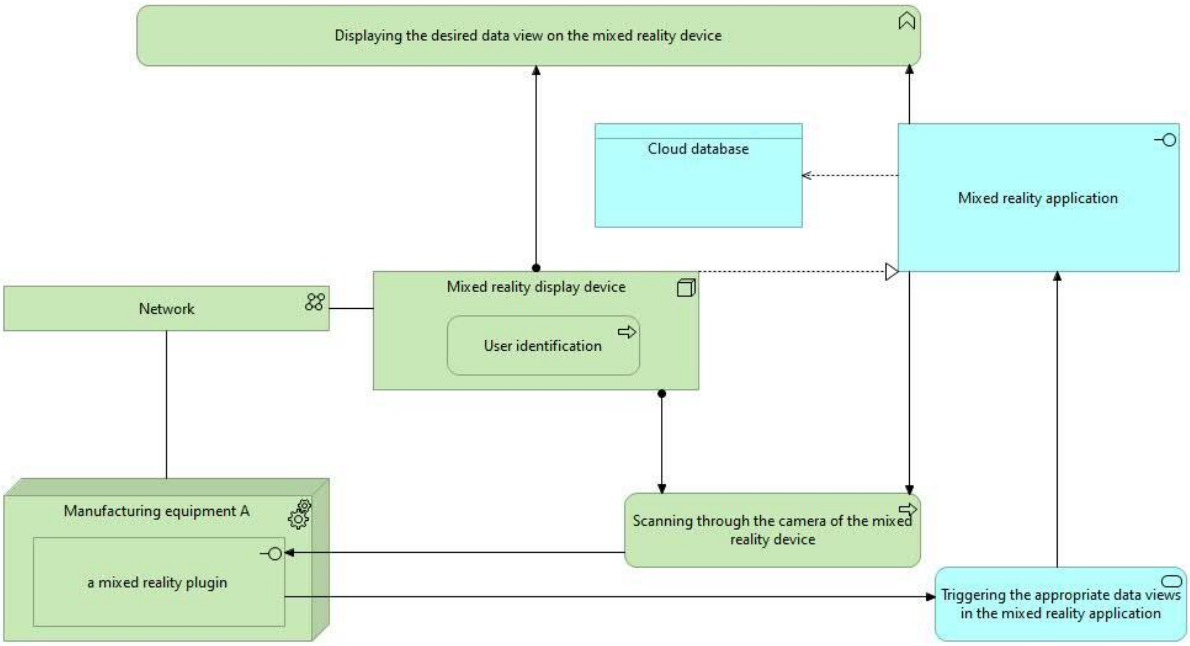

Figure 10 The interfacing between a piece of equipment in the learning factory and the mixed reality view displayed on an appropriate device. The manufacturing equipment can, in theory, be any physical entity of the learning factory.

4.3.4. Different Data Views for Different Stakeholders

In the following, the data views will be presented from the viewpoints of different stakeholder groups of the learning factory, including students, teaching staff, researchers, laboratory personnel and administration. Some of the views overlap depending on the situation, while other views are unique for one stakeholder group. It should also be noted that people within a specific stakeholder group may need different data views. This fact is especially true in university settings where teachers and researchers have different focus areas and interests.

Some of the views are not fully applicable to mixed reality use yet, but essential data views of the cyber-physical learning factory, nonetheless. The key to this aspect is that the data view is useful to the stakeholder group in question, thus adding value to the learning factory and the work of the stakeholders in question.

4.3.4.1. Students

Students are perhaps the most straightforward stakeholder group to model as they are a relatively large group with similar interests. Naturally, the content taught in the factory depends on the study program. As there is no data yet on how different study programs may use the learning factory in the future. Neither was there enough data acquired from students with different backgrounds to predict the desires of these people. Thus, the model presented in Figure 11 focuses on the needs of engineering and manufacturing students. Some of the views could be purely for practice. For example, communicating with an expert or consultant would not necessarily have to involve an external consultant. Instead, one student could act as the operator seeking help, while another student would take on the role of the consultant.

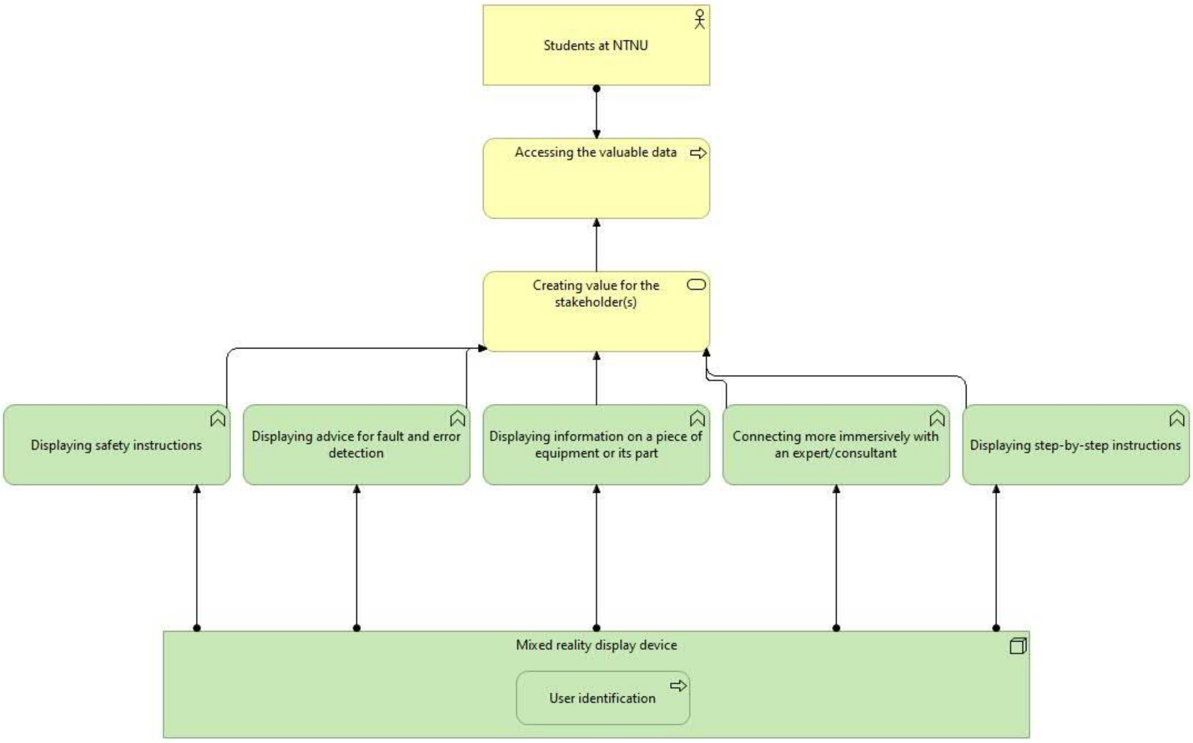

Figure 11 The envisioned data views of the learning factory for manufacturing students. The views could be modified depending on the study program. The same concept could be modified for possible industrial trainees involved as well.

4.3.4.2. Teaching Staff

The teaching at NTNU varies significantly depending on the course in question. Thus, different teachers may have very different needs when it comes to the utilisation of the learning factory. It is impossible to determine just a few standard data views to all the teachers. Thus, the model presents various data views for teachers involved in the manufacturing subjects. Not all those teachers may need all the views, however. This model tries to give a good overview.

Besides, not all data may necessarily be prudent to display through mixed reality. Some may be useful to view off-site from the learning factory. Some views, on the other hand, can be viewed both at the location through mixed reality or other devices or from other places remotely. However, the latter option requires adequate access to different solutions and platforms.

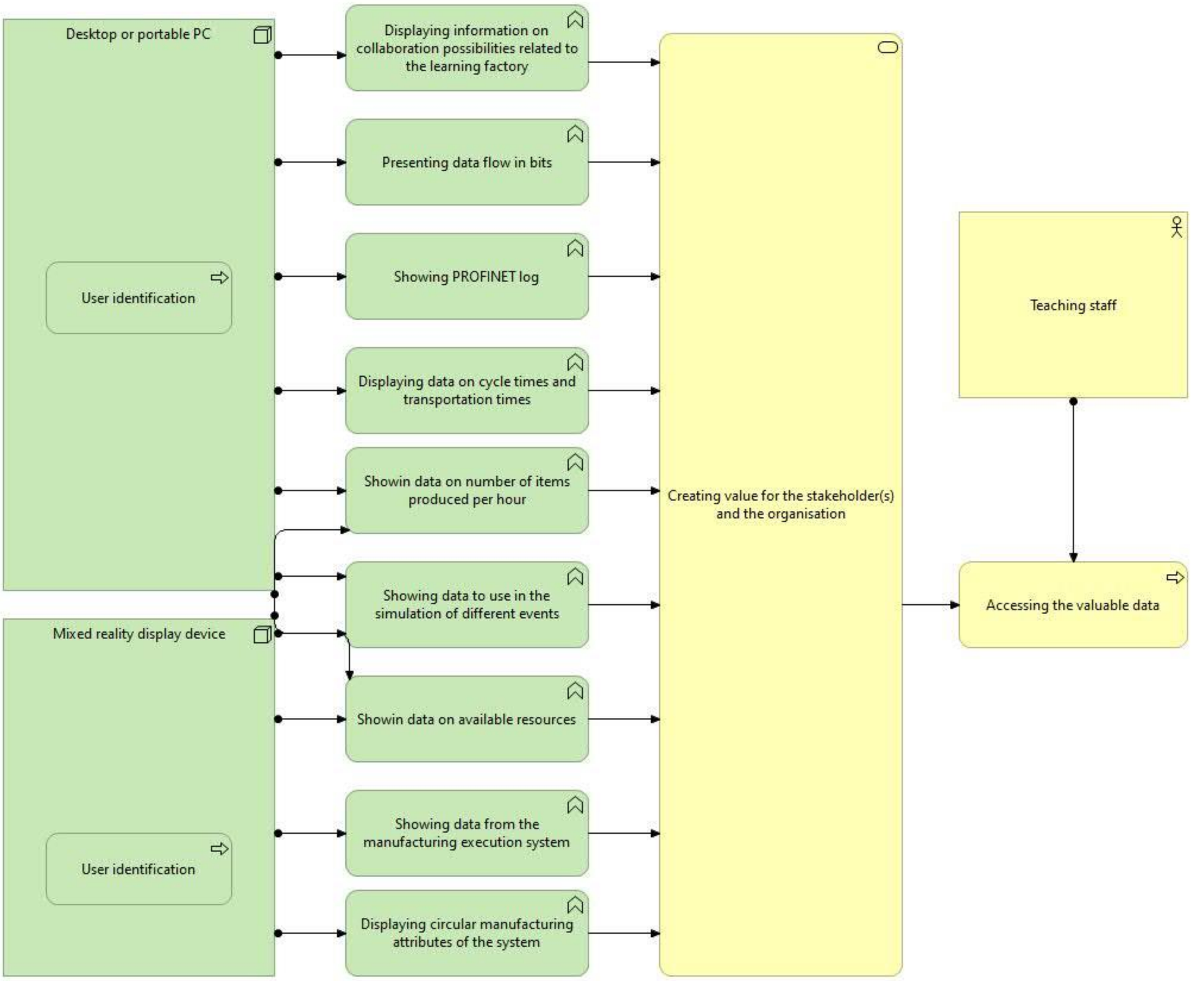

Figure 12 The envisioned data views of the learning factory for the teaching staff. Ideally, a single teacher would get all of these data views, but they would be optimised to each person individually.

4.3.4.3. Researchers

Similarly, with the case of teaching staff, researchers are often focused on specific fields of expertise. Thus, each researcher may need an individual data view. It should be noted that in a university setting, many researchers have double roles as teachers as well. Thus, the data view may need to change from day to day and depending on the activity.

Like in the previous example, in this case (Figure 13), not all data may necessarily be prudent to display through mixed reality. Some of the data views may be useful to be shown both in the factory through mixed reality and remotely by PC or similar device.

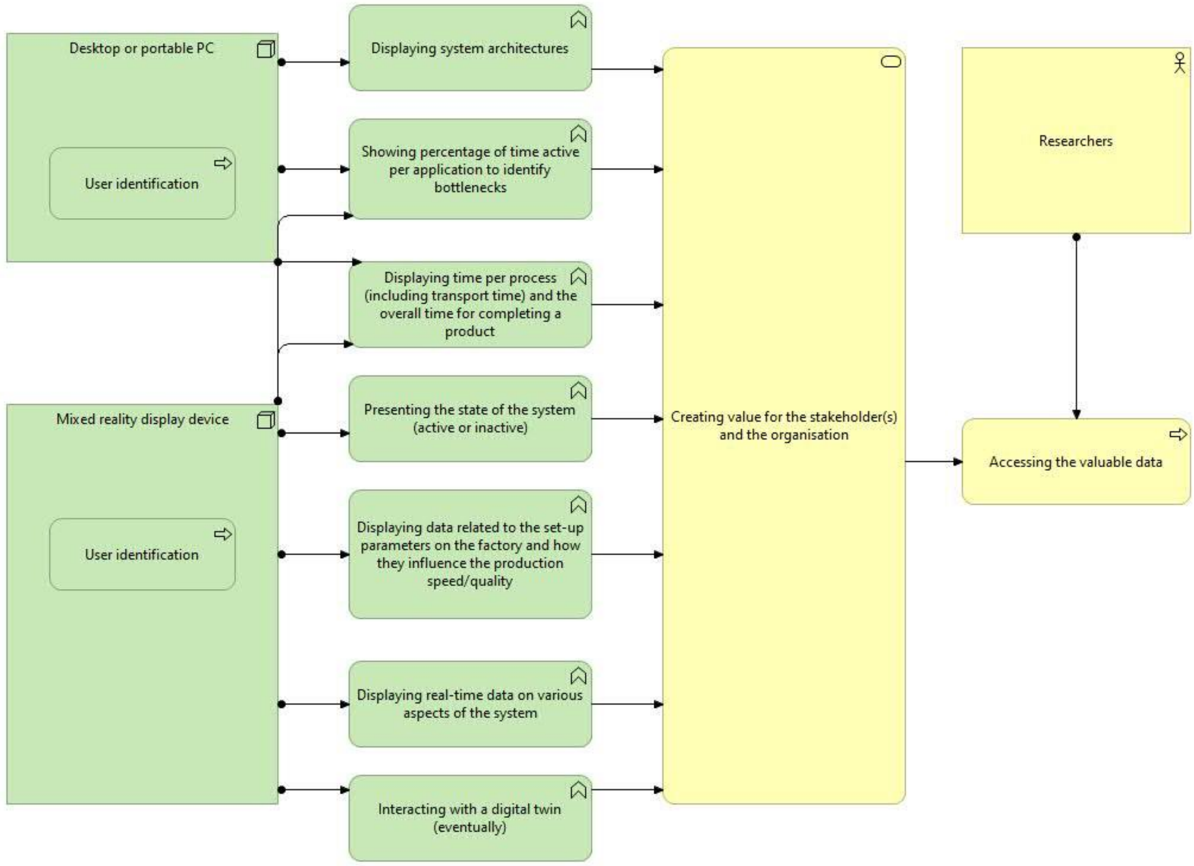

Figure 13 The envisioned data views of the learning factory for the researchers at NTNU Gjøvik. Ideally, not all researcher would be presented with all these data views. They would be optimised to each person depending on their needs.

4.3.4.4. Laboratory Personnel

The laboratory personnel are often involved in the upkeep and maintenance of the learning factory, thus requiring information related to those aspects. In Figure 14, displaying data for the maintenance and cleaning of the learning factory are clumped together as one but views concerning those aspects are almost limitless from the state of batteries and cleaning agents needed, to amount of force required to twist a bolt.

On the other hand, if a laboratory engineer needs help with a problem that they are not familiar with, mixed reality can help them communicate more effectively with an expert or consultant. In the case of the learning factory at NTNU Gjøvik, the laboratory engineer could contact an expert at Festo. Mixed reality would allow the laboratory engineer to share their view with the expert, making it easier for the expert to guide the laboratory engineer though their problem. Thus, the issue would most likely be solved more quickly and more cost-effectively as the Festo expert would not need to travel to Gjøvik to solve the problem.

Laboratory personnel are also often in charge of presenting the laboratories to different outside visitors so they may need views to aid in that aspect as well. The visitors may require individual views as well if they should be provided with access to mixed reality properties.

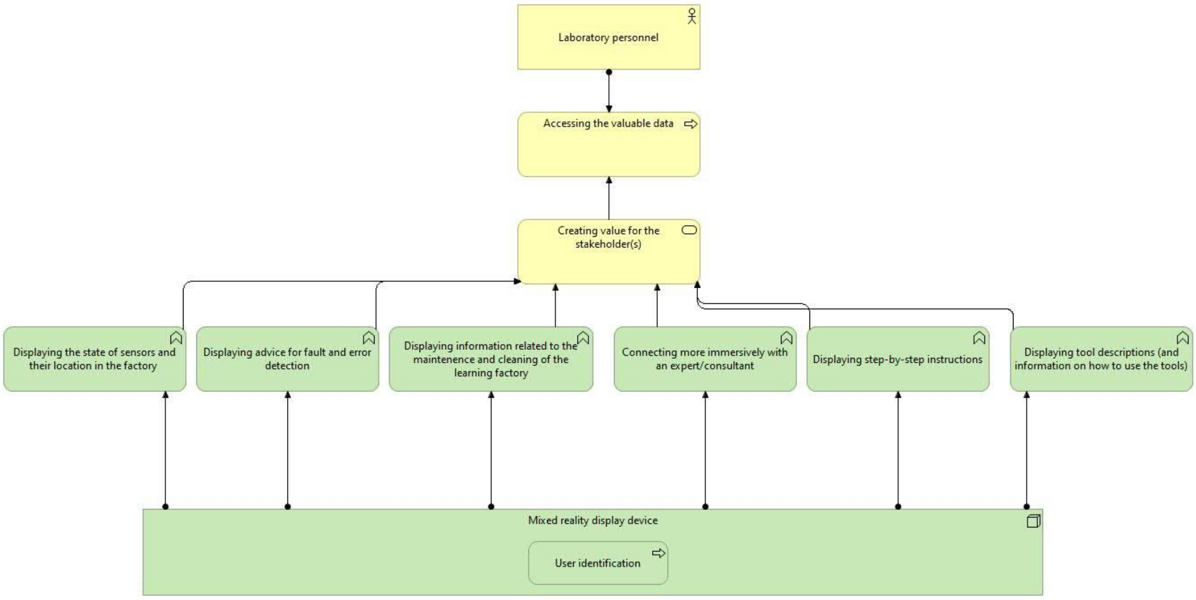

Figure 14 The envisioned data views of the learning factory for the laboratory personnel at NTNU Gjøvik. For example, the maintenance view can include many different views from the state of batteries, to exact instructions to specific problems.

4.3.4.5. Administration

From an administrative point of view, there exists a need for the data on how the revolves the learning factory can function more effectively in day-to-day activities and how it can be used in general, all from a holistic point of view. Examples of these kinds of views include information on what the factory and the people involved in it can do. Thus, when there is a specific need concerning the factory, the people in charge can determine the best person to handle the issue.

As in some of the previous cases, not all data may necessarily be prudent to display through mixed reality. Figure 15 depicts this scenario in more detail.

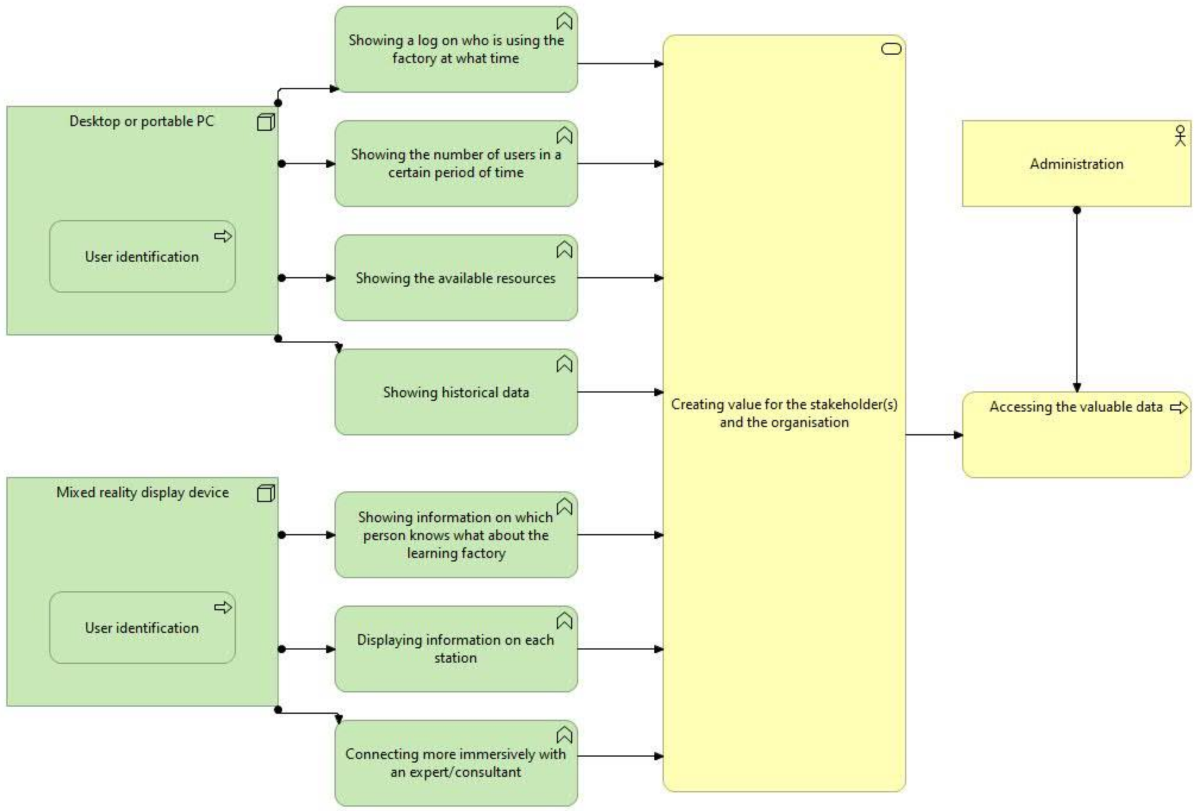

Figure 15 The envisioned data views of the learning factory from an administrative viewpoint. The administration would require data involving the users of the learning factory, as well as the resources and capabilities involved. The administration does not necessarily mean the administrative personnel of the university. However, the data can be useful to different people acting in different roles, requiring different data at different times.

5.3.4.6. Further comments

A higher level, more holistic version of the models picturing the mixed reality aspect and the stakeholders can be found in Appendix F, on page 85.

Besides the viewpoints presented in this section, there are many other viewpoints to consider when inspecting the learning factory from a holistic viewpoint. These include, among others, the information technology division of the university, data analysts and different external stakeholders, such as industry and other participants to the MANULAB infrastructure. However, those stakeholders are outside the scope of this study. They may be involved in architectural design in the future.

The results of this work are not very comparable to other similar studies made previously, as very few similar publications have been published. Similar data has not been published either, at least in a form that is accessible outside of specific organisations.

5. Discussion

In the introduction, three research questions were presented. The first question asked how mixed reality can be utilised to enhance the use of the cyber-physical learning factory at NTNU Gjøvik. The second question inquired what kind of data the different stakeholders need from the cyber-physical learning factory at NTNU Gjøvik. The last research question queried whether an enterprise model can be created based on these scenarios.

Learning factories are places for education, research and training in manufacturing and factory-related subjects. When boosted with mixed reality properties, they can provide adequate facilities for hybrid learning and enhanced research. [11] There are plenty of possibilities to utilise mixed reality to enhance the cyber-physical learning factory at NTNU Gjøvik. The students can use it in order to understand various processes, systems and data. A learning factory can be an excellent way to learn in and about complex systems. [54]

With its ability to expand the spatial perspective, mixed reality can be used to break up the physical limitations of the cyber-physical learning factory [45, 54]. Thus, the way a factory, or a manufacturing company, influences the outside world or the way outside forces influence the factory, can be visualised. This element can mean visualising and studying different global phenomena, such as environmental impacts or material flows. Similarly, some product or machine characteristics options and modifications can be simulated without needing to acquire them physically [45, 54]. Finally, emergencies or process break downs can be experienced and trained in a safe environment. In the same way, cybersecurity threats, such as hackings can be practised.

The second research question inquired what data the different stakeholders need from the cyber-physical learning factory at NTNU Gjøvik. This question is hard to answer shortly and in an all-encompassing manner. Based on the information gathered from the different stakeholders during this study, it can be stated that the data requirements differ very much depending on the person using it. The same person also often needs different data depending on the task they are performing. The data needs may even be individual depending on the person involved, not only designed a specific stakeholder group in mind. However, no adamant conclusion can be made on this issue purely based on this study as the number of people participating in the organised surveys was insufficient.

The last research question queried whether an enterprise model could be created around the themes of the first two questions. Based on the results, the answer to this question is at least a partial yes. The basis for the use of mixed reality has been modelled as having various stakeholder views. However, the modelling had to be performed and presented in pieces from the point of views of different stakeholders and their data needs as well as multiple levels of technical detail.

Creation of a full enterprise model that included all relevant layers and viewpoints was proven challenging. The difficulty of this task derived mostly from the report form of this thesis as well as the complexity of the topic. This thesis was written in a “paper” form, where readability suffers very quickly when large or otherwise complex models are involved. Besides, too many elements and relationships between them makes a model easily confusing. This fact is especially actual for readers who are not familiar with the fundamental concepts of enterprise architecture and modelling. Lastly, the architectures and models designed are not active or in use yet. Thus, the principles of enterprise architecture design and use have not been met.

Finally, it was hypothesised in the introduction, that the discoveries made from the three research questions relating to the learning factory and discussed above could be implemented to the real world and potential industry 4.0 environments outside of NTNU. Approaching this hypothesis is not straightforward. First, the stakeholder groups involved in this study are mostly involved within the university. Stakeholders and their need usually differ from those of manufacturing companies. As such, the easiest way to compare or try to repeat or implement the results of this study would perhaps be to other universities or research facilities with similar learning factories.

On the other hand, the stakeholder views of students and lab personnel may be possible to be transferred to the industry, at least in some degree. The data views of the students presented could be translated to as a view of an operator. Similarly, at least part of the view of the laboratory personnel could be transferred to the view of maintenance professionals.

As a final remark, it should be stated that many of the concepts presented in this work have not fully matured yet. Thus, their development requires further research and experiments by both industry and academia. The industry 4.0 paradigm is an ambitious vision of the future, but it is not guaranteed, when or in what form, it will be implanted to the industry more broadly.

5.1. Future Work

There exist many further opportunities to extend the elements of this study. The enterprise modelling can be extended to involve more internal and external stakeholder groups of the learning factory at NTNU Gjøvik. Further surveys within the stakeholder groups can be organised with more resources and thus generate actual statistically valid data. With adjustments and enhancements, the models can possibly be extended to be used in the general architecture of the university, as well and actively changed and developed. Similarly, the models can be actively used and updated according to changes and other requirements. Now they just act as pictures. Part of the study can be implemented to the world outside of NTNU, whether other universities or the industry. This study can also act as a basis for other studies in the same field, whether in enterprise modelling in industry 4.0 contexts or mixed reality separately.

6. Conclusion

This work has bound together the concepts of industry 4.0, mixed reality and enterprise architecture. It has also presented a partial enterprise architecture model of the learning factory at NTNU Gjøvik and proven that mixed reality is a valuable tool in smart factory environments. Different people, in different roles of an organisation, require different data. Therefore, various data views from the point of views of different stakeholders have been discussed and depicted in this work. Finally, it has been stated that the results of this work cannot be fully implemented to the real-world industry 4.0 environments. This statement is partly because the stakeholder groups, intentions, as well as goals of a university often differ from those of an industrial company.

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Appendix A: Questions for Students

Table 1. Questions presented for student via a written online questionnaire

Number	Question	Answering options
Question 1	What is your academic/professional background?	Engineering/ Design/ Computer science/ Other
Question 2	Are you familiar with the concept of mixed reality?	Yes/ No
Question 3	How have you become familiar with it?	Studies/ Work/ Games/ Social media/ I don't know what MR means!
Question 4	Can you imagine a situation in your current or future work where mixed reality could be helpful for you? Please elaborate with a sentence or two.	A fill in box. Answer up to the participant
Question 5	Let's imagine you work in a cyber-physical, smart factory environment. Which of the following (device) functions would you find useful?	Displaying information about a piece of equipment (or its part)/ Displaying safety instructions/ Displaying maintenance instructions/ To help a maintenance professional or a service provider etc. guide you through your problem/ Displaying advice for error and fault detection/ More in-depth collaboration between design and production/ Collaborative productive/ Other
Question 6	If you could choose, would you prefer to use a handheld (e.g. tablet, phone) or wearable (e.g. AR glasses) device?	Handheld/ wearable/ Depends on the situation/ I don't have a preference

Appendix B: Questions for Staff

Table 2 Questions presented to the staff at NTNU Gjovik involved with the cyber physical-learning factory. Questions presented either in a face to face interview or via a written online questionnaire. In the questionnaire, questions 2, 3 and 4 were open-ended questions.

Number	Question
Question 1	What is your role at NTNU?
Question 2	If you were at the learning factory in a teaching role, what kind of data of the factory would be useful to you? (If this isn't relevant to you, please leave this empty)
Question 3	While maintaining the learning factory, what kind of data would you like to view? (If this isn't relevant to you, please leave this empty)
Question 4	What kind of data regarding the learning factory would be useful to your own work?
Question 5	If you could choose, would you prefer to use a handheld (e.g. tablet, phone) or wearable (e.g. AR glasses) device? Or would it depend on the situation you were in?

Appendix C: Answers to the Questionnaire for Students

Table 3 The answers to the questionnaire aimed at students

#	What is your academic/professional background?	Are you familiar with the concept of mixed reality?	How have you become familiar with it?	Can you imagine a situation in your current or future work where mixed reality could be helpful for you? Please elaborate below with a sentence or two.	Let's imagine you work in a cyber-physical, smart factory environment. Which of the following (device) functions would you find useful?	If you could choose, would you prefer to use a handheld (e.g. tablet, phone) or wearable (e.g. AR glasses) device?
1	Engineering, Design	Yes	Studies, Games	YES	Displaying information about a piece of equipment (or its part), Displaying safety instructions, Displaying maintenance instructions, Being able to maintain parts of the factory of-site, Being able to connect to a maintenance professional or service provider and share your view with them in real time, so they can guide you through your problem, Displaying advice for error and fault detection, Collaborative design of products, More in-depth collaboration between design and production	Depends on the situation.
2	Other	Yes	Studies, Games	Yes I can, mainly in the training phase of any job where mixed reality can provide extra information to preform the job. This can also be used in maintenance where data on the machine can be displayed without requiring the mechanic to remember ever detail	Displaying information about a piece of equipment (or its part), Displaying safety instructions, Displaying maintenance instructions, Being able to maintain parts of the factory off-site, Being able to connect to a maintenance professional or service provider and share your view with them in real time, so they can guide you through your problem, Displaying advice for error and fault detection, Where collaborative action is required mixed reality is only as valuable as the strength of data communication, if the maintenance professionals can highlight the parts of the machine that need to be adjusted it would make for a more smooth process	Wearable
3	Engineering	No	I don't know what mixed reality means!	The topic is so new to me so unfortunately nothing comes to mind	Displaying information about a piece of equipment (or its part), Displaying safety instructions, Being able to connect to a maintenance professional or service provider and share your view with them in real time, so they can guide you through your problem, Collaborative design of products, More in-depth collaboration between design and production	Handheld
4	Engineering	No	I don't know what mixed reality means!	N/A	Displaying information about a piece of equipment (or its part), Being able to connect to a maintenance professional or service provider and share your view with them in real time, so they can guide you through your problem, Displaying advice for error and fault detection	I don't have a preference.
5	Other	Yes	Studies, Games	Yes, I think its the future. But the technology needs to become better and cheaper.	Displaying information about a piece of equipment (or its part), Displaying safety instructions, Displaying maintenance instructions, Being able to maintain parts of the factory off-site, Being able to connect to a maintenance professional or service provider and share your view with them in real time, so they can guide you through your problem, Displaying advice for error and fault detection	Depends on the situation.
6	Other	No	I don't know what mixed reality means!	No	Displaying information about a piece of equipment (or its part)	I don't have a preference.
7	Computer Science	No	Studies, Games	Repair work on critical components and fault finding.	Displaying information about a piece of equipment (or its part), Displaying safety instructions, Displaying maintenance instructions, Being able to connect to a maintenance professional or service provider and share your view with them in real time, so they can guide you through your problem, Displaying advice for error and fault detection	Wearable
8	Computer Science, Other	Yes	Work, Studies, Games, Social Media	Yes, i would like to work with develiping games, hence this is of interest to me	Displaying information about a piece of equipment (or its part), Displaying safety instructions, Being able to connect to a maintenance professional or service provider and share your view with them in real time, so they can guide you through your problem, Displaying advice for error and fault detection	Depends on the situation.
9	Other	Yes	Work, Studies, Games	For me it starts with tasks at home, giving instructions in controlling media, power consumption and tasks normally performed by craftsmen. I also see this as a valid way of medical diagnosis and follow up. In my job, I'm not able to see the present advantage, but it would be nice to be connected to a decision assistance, giving compliance (law) and technical information. Also, my subordinates will benefit from such systems in addition to more specific information.	Displaying information about a piece of equipment (or its part), Displaying safety instructions, Displaying maintenance instructions, Being able to maintain parts of the factory off-site, Being able to connect to a maintenance professional or service provider and share your view with them in real time, so they can guide you through your problem, Displaying advice for error and fault detection, Collaborative design of products, More in-depth collaboration between design and production	Depends on the situation.
10	Engineering	Yes	Work, Social Media	It's possible to present how to use products or how to maintenance or set up machine	Displaying information about a piece of equipment (or its part), Displaying safety instructions, Displaying maintenance instructions, Being able to maintain parts of the factory off-site, Being able to connect to a maintenance professional or service provider and share your view with them in real time, so they can guide you through your problem, Displaying advice for error and fault detection, Collaborative design of products, More in-depth collaboration between design and production	Handheld
11	Engineering, Design	Yes	Studies	I do belive that utilizing mixed reality could be advantageous. One example would perhaps be a visit to a manufacturing company. As a visitor/student trying to gain knowledge about how machinery or different system, through the visit, mixed reality could provide a visual illustration around the envoriment and such making it easier to look at the bigerpicture (or the company as a whole).	Displaying information about a piece of equipment (or its part), Displaying safety instructions, Being able to maintain parts of the factory off-site, Being able to connect to a maintenance professional or service provider and share your view with them in real time, so they can guide you through your problem, Collaborative design of products	Handheld
12	Engineering	No	I don't know what mixed reality means!	N/A	Displaying information about a piece of equipment (or its part), Displaying safety instructions, Displaying maintenance instructions, Being able to maintain parts of the factory off-site, Being able to connect to a maintenance professional or service provider and share your view with them in real time, so they can guide you through your problem, Displaying advice for error and fault detection, Collaborative design of products, More in-depth collaboration between design and production	Depends on the situation.
13	Computer Science, Design	Yes	Games	N/A	Displaying information about a piece of equipment (or its part), Displaying safety instructions, Displaying maintenance instructions, Being able to maintain parts of the factory off-site, Being able to connect to a maintenance professional or service provider and share your view with them in real time, so they can guide you through your problem, Displaying advice for error and fault detection, Collaborative design of products, More in-depth collaboration between design and production	Depends on the situation.
14	Engineering	Yes	Studies, Games	N/A	Displaying information about a piece of equipment (or its part), Being able to connect to a maintenance professional or service provider and share your view with them in real time, so they can guide you through your problem, More in-depth collaboration between design and production	Depends on the situation.

Appendix D: Answers gathered from the staff

Table 4. Information gathered from staff on the topic what kind of data they would need from the learning factory

Activity in the learning factory	Desired data
Teaching	• PROFINET log • data flow in bits • cycle time • transportation time • number of items produced per hour • collaboration possibilities • theory to practice • available resources • MES data • data to use in the simulation of different events • circular manufacturing attributes of the system • training to work in the factory step-by-step
Research	• any sorts of data related to the set-up parameters on the factory and how they influence the production speed/quality • system architectures • state of the system (active or inactive) • time per process (including transport time) • the overall time for completing a product • percentage of time active per application to identify bottlenecks • real-time data on various aspects of the system • creation of a digital shadow and eventually a digital twin
Maintenance of the learning factory	• number of users • run-time • how long the different modules and tools have been running • the state of sensors and their location in the factory (ideally more sensors should be embedded to utilise predictive maintenance on the CNC milling machine and robots) • detailed information on how to work in the factory • information on the manual labour needed when working with something specific, e.g. the required amount of force
Other aspects of the factory	• helping visitors in the lab when the staff is unavailable or the learning factory is offline • properly functioning and user-friendly manuals • cleaning instructions • state of batteries • tool descriptions
Administration	• which person knows what about the factory? • Who is using the factory at what time? • number of users • historical data • available resources • station information • expert consultation
A handheld or wearable device?	• depends on the situation – 3 answers • handheld – 1 answer • wearable – 2 answers

Appendix E: The Symbols and Elements of the ArchiMate Enterprise Modelling Language

Figure 16 Legend of the different symbols and element of the ArchiMate enterprise modelling language [85]

Appendix F: Model on Interfacing and Information Flow

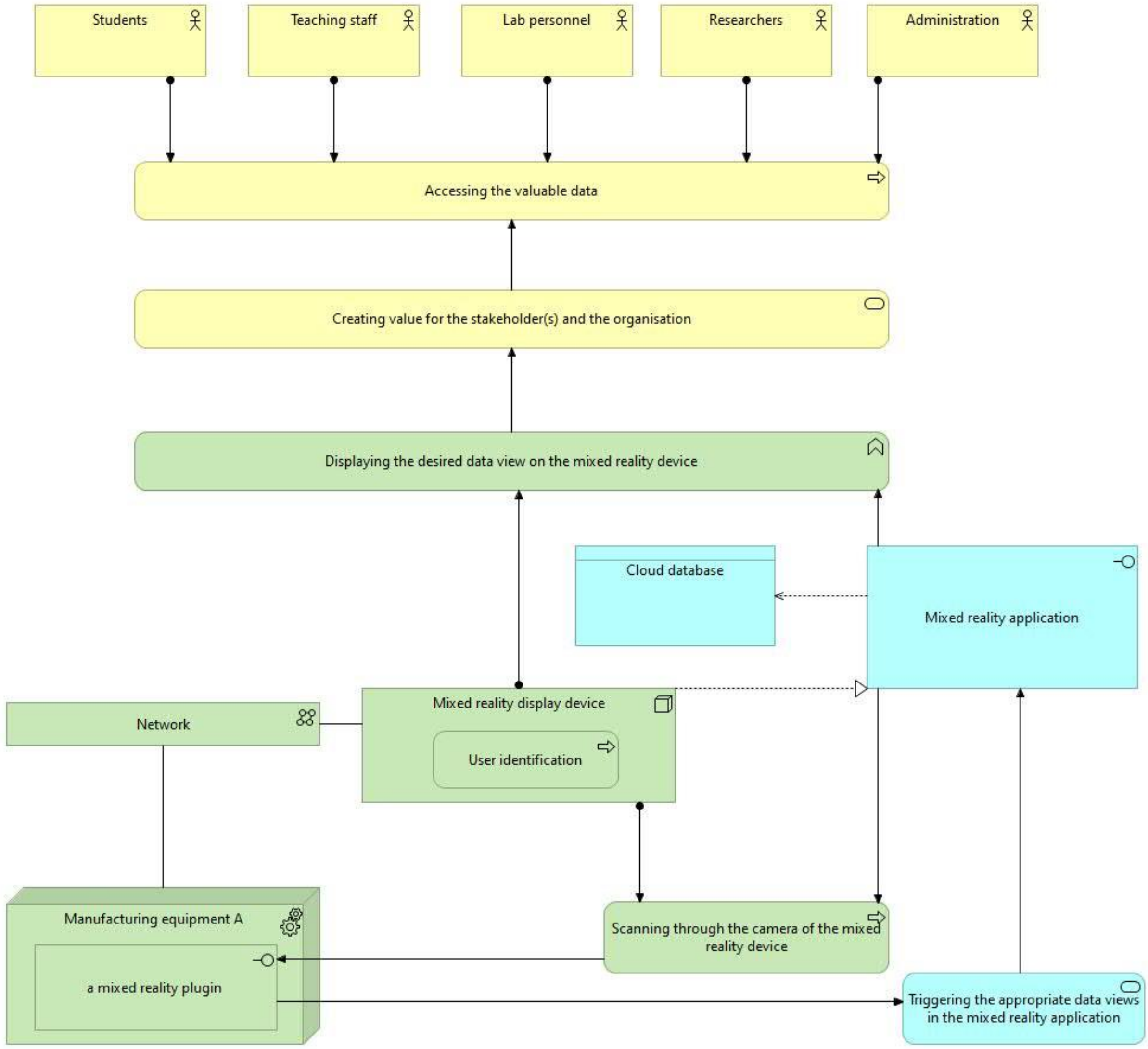

Figure 17 A higher level, more holistic version of the models picturing the mixed reality aspect and the stakeholders.

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