Remote Monitoring and Visualization of Inventory Levels

A Case Study at Virtual Manufacturing

Master's thesis in Production Engineering

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Cover: Illustration of three areas covered in the thesis. Physical inventory, data transmission, and data visualization.

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Abstract

Industry 4.0 and mass customization sets high requirements on flexibility of inventory management. When these requirements are unfulfilled, material shortages can occur, which can result in production stoppages. By monitoring inventory levels, the risk of such shortages occurring can be reduced. The physical inventory must, however, correspond to the monitored, digital representation of the inventory. Existing solutions for avoiding inaccuracies of inventory levels are limited, and technologies for register inventory levels of boxes stored in flow racks were therefore explored in this thesis. Further, the aim was to integrate one, or several, of the explored concepts in a real-world system and visualize the data into a digital twin of the system to enable remote monitoring. The methodology was based on a theoretical framework and a mapping of technologies, followed by a concept creation phase and integration and visualization of the concepts in a digital twin. Throughout the project, a case study was used to identifying concept requirements and evaluating the concepts on a real-world system. Technologies found suitable for register inventory levels and enable remote monitoring are barcodes, Radio Frequency Identification (RFID), weight sensors, distance sensors, and contact sensors. The two concepts that fulfill the requirements from the case study are based on a weight sensor, respectively a distance sensor. In the concepts, data from the sensors are sent by WiFi to an Internet of Things (IoT) platform and then integrated and visualized in a digital twin with a low level of data integration. To conclude, there are ways to monitor inventory levels remotely in a flow rack. An ultrasonic distance sensor is proved to satisfyingly measure the correct number of boxes stored in a flow rack. However, the concept requires well-followed procedures to minimize the risk of human errors and thereby avoid inaccuracies.

Keywords: Inventory Management, Inventory Inaccuracies, Remote Monitoring, Sensors, Case Study, Digital Twin, Industry 4.0, Visualization

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Anna Kindlundh & Sanne Larsson, Gothenburg, May 2021

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List of Abbreviations

BDA Big Data Analytics. 1, 8, 9, 26, 58
BOM Bill Of Material. 2, 34–36

CPS Cyber-Physical Systems. 1, 2, 8, 11, 26

EOQ Economic Order Quantity. 6
ERP Enterprise Resource Planning. 2, 6, 26, 35–37, 58

IoT Internet of Things. 1, 2, 7, 8, 15, 16, 18–20, 26, 27, 46, 54, 59
IR Infrared light. 17, 27, 44

JIT Just In Time. 6

MQTT Message Queue Telemetry Transport. 20
MRP II Manufacturing Resource Planning. 6

POI Point Of Interest. 37, 50

QR Quick Response. 14, 22

RFID Radio Frequency Identification. 7, 13–15, 18, 19, 27, 38, 40–42, 46–48, 52, 54, 59

SCM Supply Chain Management. 1, 6, 15, 38

UDS Ultrasonic Distance Sensors. 17

WLAN Wireless Local Area Networks. 19, 21
WSN Wireless Sensor Network. 16, 19, 20, 27

1
Introduction

The following chapter describes the background of this project, the project aim, and its limitations. It is followed by a specification of the issue under investigation.

1.1 Background

The fourth industrial revolution is a new paradigm shift called Industry 4.0 (Kumar, Zindani, & Davim, 2019). In the third industrial revolution, machines were made to automate production but not allowing for much variability (Kumar et al., 2019). In Industry 4.0, mass customization is enabled to meet the change in customer demand (Grabowska, 2020; Kumar et al., 2019). Fatorachian and Kazemi (2021) describe four key Industry 4.0-enabling-technologies, the Cyber-Physical Systems (CPS), Internet of Things (IoT), Big Data Analytics (BDA), and cloud computing technologies. Technologies that all are impacting the supply chain in different ways (Fatorachian & Kazemi, 2021). CPS and cloud computing technologies can enhance collaboration and cooperation within the supply chain (Fatorachian & Kazemi, 2021). One potential impact of the IoT is the enablement to monitor and communicate real-time performance within different segments in the supply chain (Fatorachian & Kazemi, 2021). The forecasting and planning within the supply chain could potentially be improved by the use of BDA (Fatorachian & Kazemi, 2021). Using Industry 4.0-enabling-technologies can also aid the social, ecological, and economical development of the supply chain (Khan, Ahmad, & Majava, 2021).

One part of the Supply Chain Management (SCM) at a company is the inventory system, entailing to manage inventories of intermediate products and raw materials (Nasrabadi & Mirzazadeh, 2016). With an increased demand for quality products, sold at the best price, and available with short lead times, the determination of product status and location is critical to a company's success (Yao & Carlson, 1999). By maintaining an optimal inventory level, high costs can be minimized. For example, the inventory carrying costs, expensive last-minute purchases, and cost of obsolete inventory can be held to a minimum level (Jonsson & Mattsson, 2009). To ensure the correct determination of available materials, the capabilities brought by the four Industry 4.0-enabling-technologies, named earlier, can be utilized (Fatorachian & Kazemi, 2021).

Inadequate inventory management, can result in material shortages as the correct determination of available materials is not ensured (Nemtajela & Mbohwa, 2017). According to a company that assembles modular products, reasons for material shortages can be an incomplete Bill Of Material (BOM), deficient update of the inventory in the Enterprise Resource Planning (ERP) system, too late purchases, and disarray at the storage of material (J. Sigvardsson, personal communication, February 27, 2021). Other reasons that also can lead to incorrect accounted inventory on hand are if the inbound deliveries are reported in incorrect quantities (Jonsson & Mattsson, 2009). Not reporting wastage and material withdrawals, or reporting incorrect quantities, increases the risk of faulty accounted inventory on hand (Jonsson & Mattsson, 2009).

Industry 4.0 and mass customization entail high requirements on the flexibility of the inventory management (Grabowska, 2020), as the demand becomes uncertain (Nemtajela & Mbohwa, 2017). To increase flexibility and prevent material shortages, Industry 4.0-enabling-technologies can be used. For example, CPS and IoT can be used to connect the virtual and physical worlds to improve visualization and enabling remote monitoring of inventory levels (Fatorachian & Kazemi, 2021). With remote monitoring, the time needed for stocktaking and administrative tasks can decrease. One way to reflect the real-time data from the physical world to the virtual world is by using a digital twin (Kumar et al., 2019; Yuan, 2020). Using a digital twin could result in effective monitoring and control of data from real-time events (Kumar et al., 2019).

However, the amount of practical examples of concepts that take advantage of Industry 4.0-enabling-technologies to prevent material shortages and enable remote monitoring of inventory levels is limited. Hence there is a need for research in this area to examine the possible opportunities and drawbacks with such a concept.

1.2 Aim

The project aims to explore different technologies that can be used for inventory management and evaluate and integrate an appropriate concept on a real-world system subject to the inaccuracies of inventory levels. Furthermore, the aim is to visualize the data to take the first steps towards a digital twin of production.

1.3 Limitations

The inventory monitoring system is not guaranteed to be applicable for all types of existing inventory systems. An inventory buffer for C-parts, such as fasteners, stored in flow racks in the packaging delivered from the supplier is the system investigated. The inventory monitoring system must support the future digital transformation of a production site and, not only, solve the problem with inaccurate inventory levels.

The data integrated into a digital twin will only address the first maturity stage of analytics, describing the present result. Additionally, when potential concepts of an inventory monitoring system are evaluated from a cost perspective, only the material cost is considered, and by that, not the implementation, installation, and running cost.

1.4 Specification of Issue Under Investigation

By refining the aim of the project, the following research questions have been formulated and are expected to be answered through the project:

RQ1. Which technologies are suitable for registering and monitoring inventory levels for real-world systems subject to inaccuracies of inventory levels?

RQ2. How could a concept of an inventory monitoring system be designed, using one or several technologies, to monitor inventory levels remotely?

RQ3. How can a concept be integrated into a real-world system and visualized in a digital twin?

2
Theoretical Framework

The Theoretical Framework stands for the theory related to this project, including technical information and state-of-the-art knowledge relevant to the subjects presented. First, information regarding inventory management is introduced and followed by Industry 4.0 and its related concepts. Thereafter, technologies for register inventory levels, transmit data, and visualize data are described. The last part of the chapter is the result of the market analysis, presenting concepts of inventory monitoring systems available on the market by other companies. An overview of the parts included and how they relate to each other are presented in Figure 2.1.

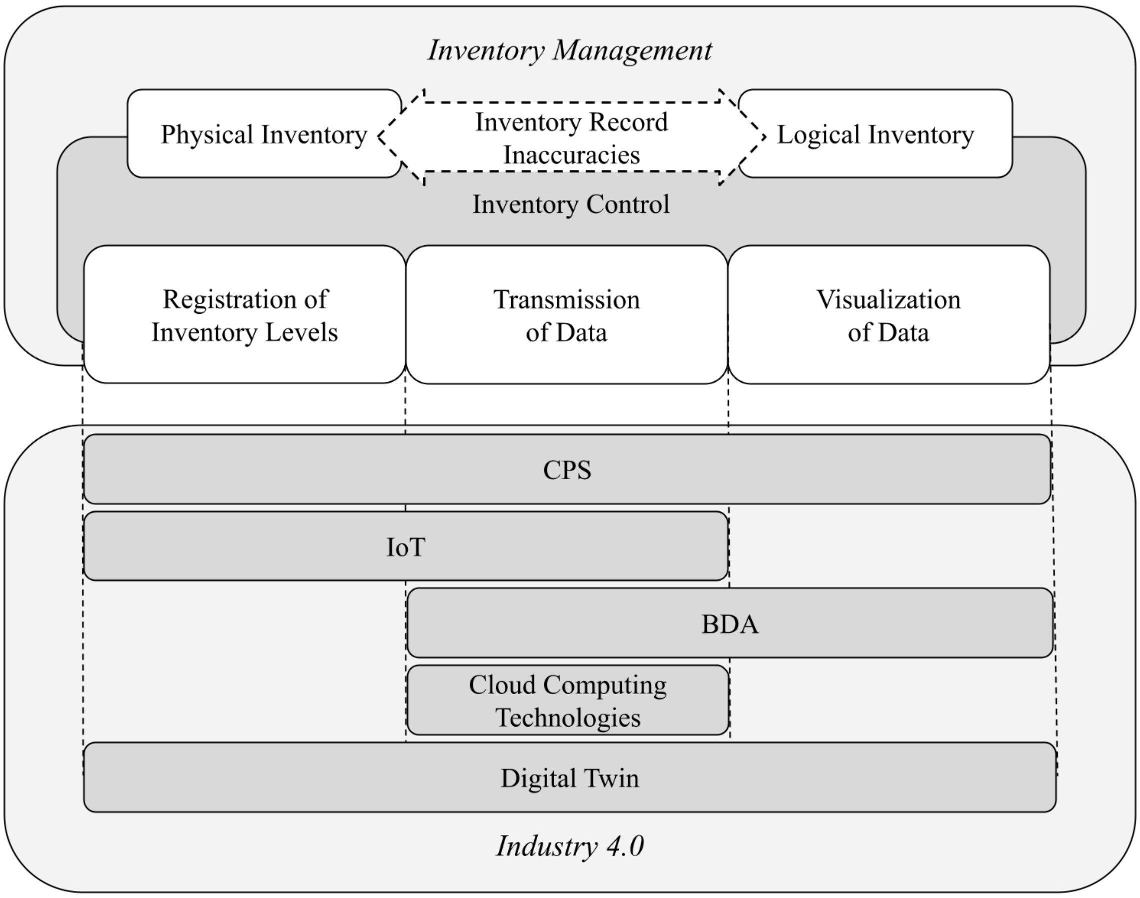

Figure 2.1: Schematic illustration of the overall relationship between the subjects in Chapter 2.

2.1 Inventory Management

SCM consists of several business processes, one being inventory management (Prater & Whitehead, 2013). Inventory management can, in turn, be divided into inventory balancing, inventory planning, and inventory control (Relph & Milner, 2019). Relph and Milner (2019) describe inventory balancing to be about having the right amount of inventory to avoid, for example, lost orders and money tied up. Throughout organizations, it must therefore be possible to monitor the inventory levels so that actions can be made when inventory is not within the optimum levels (Relph & Milner, 2019). How to set these optimal inventory levels is what inventory planning concerns (Relph & Milner, 2019). Inventory control involves how to manage the physical inventory, the logical inventory, and how to ensure that these two matches (Prater & Whitehead, 2013; Relph & Milner, 2019). The following sections describe different inventory control techniques and how inventory record inaccuracy emerges.

2.1.1 Inventory Control Techniques

Various ways of controlling different articles exist, and to make it easier, they can be grouped and use the same technique for controlling (Axsäter, 2015). For example, parts in inventory can be divided into three groups, depending on their annual usage spend, using ABC classification (Relph & Milner, 2019). Group A consists of few parts of high value and importance (Relph & Milner, 2019). Parts of less value, compared to parts in group A, are categorized in group B (Relph & Milner, 2019). The number of parts in group B is usually more, in comparison to group A (Relph & Milner, 2019). In group C, there are several different parts with low value that have a low cost to have on stock (Relph & Milner, 2019), like fasteners. Parts classified in group C are called C-parts (Relph & Milner, 2019). One wants to minimize time spent on managing these parts and buying them in larger quantities (Relph & Milner, 2019).

Widely used techniques for inventory control is Economic Order Quantity (EOQ), Just In Time (JIT), Manufacturing Resource Planning (MRP II), and ERP (Prater & Whitehead, 2013). EOQ determines the order quantity to minimize ordering cost, inventory carrying costs, and calculate the reorder point (Prater & Whitehead, 2013). Constant demand is considered when calculating the EOQ (Prater & Whitehead, 2013). JIT strives to reduce inventory and its carrying costs by, for example, shorten the lead-times and reducing the lot size (Prater & Whitehead, 2013). MRP II is used for planning and scheduling and uses different variables for this, such as historical data and forecasts (Prater & Whitehead, 2013). MRP II is one of the techniques that can be included in the ERP (Axsäter, 2015).

ERP systems consist of modules with functions spanning over the whole company, like inventory control, materials management, production management, warehouse management, and financial accounting (Ganesh, Mohapatra, Anbuudayasankar, & Sivakumar, 2014; Nettsträter, Geißen, Witthaut, Ebel, & Schoneboom, 2015). The modules and their databases are linked together into one place, making data available throughout the whole organization (Ganesh et al., 2014). Focusing on the first mentioned module, inventory control, Axsäter (2015) concludes that an inventory control system can be both manual and computerized. It can include a module of forecasting, reordering points, order quantity, and monitoring of inventory levels (Axsäter, 2015). The last is used either periodically or continuously to trigger an order when the inventory is below a certain level (Axsäter, 2015). A concept well-known and easy to implement for trigger orders is the Kanban concept (Axsäter, 2015). Traditionally, empty bins noticed by an employee trigger a signal of needed replenishment periodically (Hofmann & Rüsch, 2017). However, for several years also a so-called e-Kanban is in use and triggers an electronic signal continuously without human interaction (Hofmann & Rüsch, 2017).

2.1.2 Inventory Record Inaccuracy

A precondition for the inventory control system to work is that the input data is correct, such as the stock on hand (Axsäter, 2015). There are several reasons why physical and logical inventory does not match. Wang, Fang, Chen, and Li (2016) summarizes three central reasons to be misplacement, shrinkage, and transaction errors. Shrinkage can occur due to damage, spoilage, and theft, while transaction errors essentially occur when moving inventory, such as when receiving an order (Rekik, 2011).

To cope with these inaccuracies, one can try to prevent them by doing changes in the process like adding new technology such as Radio Frequency Identification (RFID) (DeHoratius, Mersereau, & Schrage, 2008; Rekik, 2011; Wang et al., 2016), which will be further described in Section 2.3.2. However, a solution with RFID is more profitable when the cost of the articles is higher (Rekik, 2011). Apart from adding new technologies, improvements can be done to existing procedures (Sahin & Dallery, 2009). Additionally, the presentation and labeling of articles can be improved to minimize picking and scanning errors, and operators can be trained to perform procedures correctly (Sahin & Dallery, 2009). By doing regular stocktaking, the inaccuracies can also be corrected (DeHoratius et al., 2008; Sahin & Dallery, 2009). One can also integrate the inaccuracy in the tools used for planning and decision (DeHoratius et al., 2008; Sahin & Dallery, 2009).

2.2 Industry 4.0

The concept of Industry 4.0 was officially presented as Industrie 4.0 in 2013 as a program to revolutionize the manufacturing sector in Germany (L. D. Xu, Xu, & Li, 2018). There is not a clear definition of Industry 4.0, but it strives to build intelligent networks by merging the physical and digital world and connect systems, machines and work units to make a digital transformation (Gilchrist, 2016). Industry 4.0 consists of a set of key enabling technologies, allowing for increased flexibility in production and mass customization of products (Kumar et al., 2019). Gilchrist (2016) divide these technologies into nine categories, big data and analytics, autonomous robots, simulation, horizontal and vertical integration, the industrial IoT, cyber-security, the cloud, additive manufacturing, and augmented reality.

Smart Manufacturing is sometimes also known as the fourth industrial revolution and the American version of the Industrie 4.0 program (Hofmann & Rüsch, 2017; Kang et al., 2016). It merges some of the Industry 4.0-enabling-technologies, foremost CPS, IoT, and cloud computing technologies, with existing manufacturing technologies to make it possible to make real-time decisions with accuracy (Kang et al., 2016). In the following sections, some key Industry 4.0-enabling technologies, as well as the concept of a digital twin, will be further described.

2.2.1 Cyber-Physical Systems

In 2006, the term CPS was coined (Lee & Seshia, 2017), and it is considered to be one of the core functions of Industry 4.0 (L. D. Xu et al., 2018). The use of CPS triggered the paradigm shift in companies, mainly from the manufacturing industry sector (L. D. Xu et al., 2018). CPS is closely related to IoT, as IoT often is seen as a portion of CPS (Lee & Seshia, 2017). The main difference between IoT and CPS is that CPS includes other physical systems that embed computational power beyond things connected to the Internet (Camarinha-Matos, Goes, Gomes, & Martins, 2013). CPS consists of embedded computers and networks that are used to monitor and control physical processes (Gilchrist, 2016; Lee & Seshia, 2017). The CPS is focusing on the intersection between the physical processes and the cyber, not the union of the two (Lee & Seshia, 2017). According to research, the use of CPS will enable communication between machines and decentralized control systems, making it possible to optimize production (Lee & Seshia, 2017).

2.2.2 Internet of Things

The concept of IoT emerged already in the late 1990's (Ma, 2011), and is sometimes considered to be a subset of CPS (Camarinha-Matos et al., 2013). IoT can be described as an enabler of the interconnection and integration between the physical world and the cyberspace (Fatorachian & Kazemi, 2021; Ma, 2011), associating things over the Internet (Khanna & Kaur, 2020). By connecting the physical things to the Internet, sensor data can be accessed and used to control the physical things remotely (Kopetz, 2011). Khanna and Kaur (2020) concludes that almost everything that today is existing physically, will within the next years be connected over the Internet. According to Statista (2021b), the number of IoT connected devices worldwide will increase from 8.74 billion in 2020 to 25.4 billion in 2030. The number of devices related to inventory management and monitoring stands for an increase from 175 million in 2020 to 446 million in 2030 (Statista, 2021b).

2.2.3 Big Data Analytics

Another Industry 4.0-enabling-technology is BDA, however, Bi and Cochran (2014) state that BDA is not solely a technology but more of a process to, in different ways, analyze and mine big data. The term big data began to be mentioned frequently in documents from 2011 (Gandomi & Haider, 2015), but still, there is no common definition of the concept (Bi & Cochran, 2014; De Mauro, Greco, & Grimaldi, 2016; Gandomi & Haider, 2015). Bi and Cochran (2014) describe the concept of big data to be about both the datasets' features and the different ways to process the data. The "3 V's" is also a term used to describe big data, as data with certain Volume, Variety, and Velocity gets impossible to handle with traditional methods for capturing, storing, managing, and analyzing (Gandomi & Haider, 2015; The White House, 2014).

The amount of data has over the recent years been exponentially growing (Bi & Cochran, 2014), and will continue to grow (Manyika et al., 2011; Statista, 2021d). This is due to several reasons, some being new sources of data, such as the increased amount of sensors connected in networks, and less expensive ways to collect, store, and process the data (Bi & Cochran, 2014; Manyika et al., 2011; The White House, 2014). With BDA, this data can be used to extract insights and drive decision making (Gandomi & Haider, 2015). Techniques that can be used for doing this is different analytics of text, audio, video, and social media, and various predictive analytics (Gandomi & Haider, 2015).

2.2.4 Cloud Computing Technologies

Cloud computing can be seen as a model of where computing resources such as networks, servers, storage, and applications, are shared and often outsourced to third-parties (X. Xu, 2012). The sharing enhances the accessibility of data throughout the organization and can improve decision-making and planning thanks to analytical capabilities (Fatorachian & Kazemi, 2021). It consists of several layers of services aimed at different users, such as infrastructure as a service, platform as a service, and software as a service (X. Xu, 2012). Sometimes the term cloud manufacturing is used, as a type of cloud computing focused on manufacturing (X. Xu, 2012).

2.2.5 Digital Twin

One concept which is highly related to Industry 4.0 and digital transformation, is digital twins (Kritzinger, Karner, Traar, Henjes, & Sihn, 2018; Negri, Fumagalli, & Macchi, 2017). Although the concept starts to get widely spread, there is no clear and aligned definition (Grieves, 2015; Negri et al., 2017; Tao, Qi, Wang, & Nee, 2019; Tao, Zhang, & Nee, 2019; Wright & Davidson, 2020). The definitions can vary depending on the sector, and in some cases it can also vary within the same sector (Wright & Davidson, 2020). However, the concept of digital twin origins from early 2000's when Grieves introduced the term in his course on Product Lifecycle Management at the University of Michigan (Grieves, 2015; Tao, Qi, et al., 2019). By that time, Grieves (2015) defined the concept as a "virtual, digital equivalent to a physical product" (p. 1). Some years later, in 2010, an official definition of digital twin for space vehicles was released by NASA (Negri et al., 2017).

In the following sections, different perspectives on the digital twin are described. First, the evolution of the dimensions of the concept is presented. It is followed by three definitions of a digital twin, depending on the level of integration, analytics, and maturity. Lastly, the life cycle phases of the digital twin are described.

Model Dimensions

When Grieves introduced the concept of the digital twin, he defined it as a three-dimension model, including the physical products (in real space), virtual products (in virtual space), and the connection between those two (Grieves, 2015). In the beginning, the digital twin was mainly focused on military products within aerospace (Tao, Zhang, & Nee, 2019). In recent years, the application areas for the digital twin have increased, and, consequently, so have the demands and requirements on the concept as well (Tao, Zhang, & Nee, 2019). A five-dimension model has been introduced to meet the new demands and requirements (Tao, Zhang, & Nee, 2019). With the three-dimension model as the basis, two additional dimensions are added in the five-dimension model (Tao, Zhang, & Nee, 2019). First, the services for the physical products and virtual products, enabling the implementation of easy and on-demand usage (Tao, Zhang, & Nee, 2019). Second, the digital twin data, enabling more accurate and extensive information by combining data from the physical and virtual products (Tao, Zhang, & Nee, 2019).

Level of Integration

There are other terms, beside digital twin, used to describe the concept. Digital twin, digital shadow, and digital model are terms often used as synonyms (Kritzinger et al., 2018). However, the different definitions indicates on different levels of data integration between the physical and virtual product (Kritzinger et al., 2018). Kritzinger et al. (2018) proposes a distinction between the three terms, based on their level of data integration, visualized in Figure 2.2.

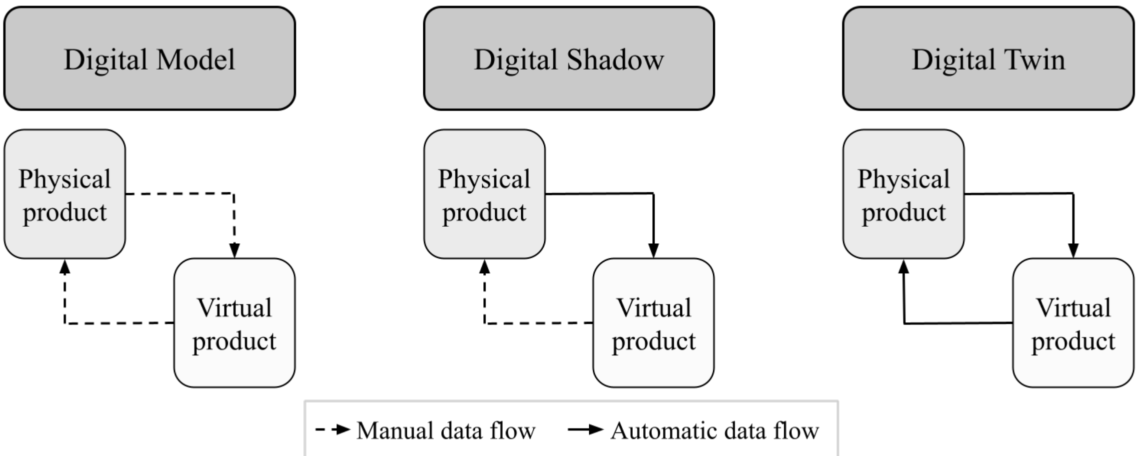

Figure 2.2: Data flow in a digital model, digital shadow, and digital twin.

A digital model is a digital representation of a physical product where all data exchange is conducted manually (Kritzinger et al., 2018). The digital model can include a comprehensive description of, for example, the physical product, simulations, and mathematical models, that does not use any automatic data integration (Kritzinger et al., 2018). The physical and virtual product has no direct affect on each other in a digital model (Kritzinger et al., 2018). A digital shadow function in a similar way as the digital model but there is an automatic data flow from the physical product to the virtual product (Kritzinger et al., 2018). The digital twin has similar functions as the digital model and digital shadow, but the data flow is automatic in both directions (Kritzinger et al., 2018). A change in the physical product will affect the virtual, and the other way around, in a digital twin (Kritzinger et al., 2018). The seamless integration that the digital twin generates between the physical and virtual world is similar to the goal of CPS (Tao, Zhang, & Nee, 2019). However, the digital twin is considered only to be a subset of the CPS (Tao, Zhang, & Nee, 2019).

Level of Analytics

A digital twin can also be defined by its level of analytics. Król and Zdonek (2020) describe five stages in which different levels of analytics maturity are fulfilled. As can be seen in Figure 2.3, the first stage is descriptive analytics, the primary source of information for the management team. Through the characterization of data and identification of patterns that the data indicates, descriptive analytics enables learning and understanding of reality (Król & Zdonek, 2020). The descriptive analytics provides an answer to what happened (Król & Zdonek, 2020). Diagnostic analytics is used to detect regularities and relationships between variables from historical data (Król & Zdonek, 2020). The diagnostic analytics describes why things happened (Król & Zdonek, 2020).

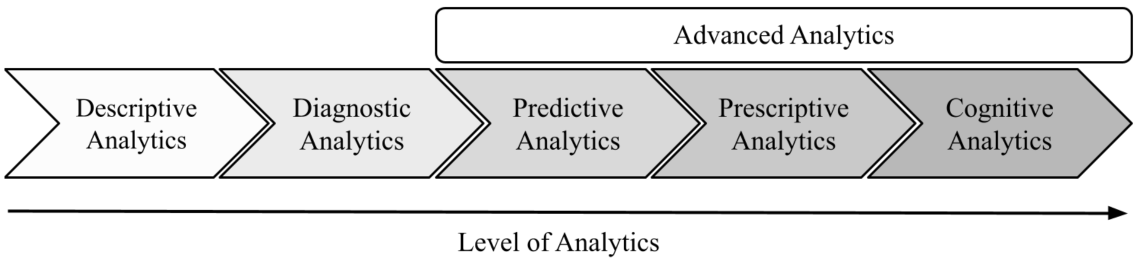

Figure 2.3: Different levels of analytics maturity.

Predictive analytics is the first stage that is defined as advanced analytics (Król & Zdonek, 2020), as seen in Figure 2.3. Predictive analytics involves analysis of both real-time and historical data to find out what may happen in the future (Król & Zdonek, 2020). Similar to predictive analytics, prescriptive analytics can also be categorized as advanced analytics (Król & Zdonek, 2020). By using machine learning and simulations, prescriptive analytics can suggest what actions should be taken (Król & Zdonek, 2020). Prescriptive analytics aims to automate the actions that are to be taken (Król & Zdonek, 2020). The last definition is cognitive analytics, also defined as advanced analytics (Król & Zdonek, 2020). Cognitive analytics is the definition with the highest level of analytics maturity (Król & Zdonek, 2020). Based on artificial intelligence technologies and advanced data analysis, cognitive analytics automates decision-taking and increases the efficiency of the decisions taken (Król & Zdonek, 2020).

Level of Maturity

Besides the level of data integration and analytics, there is another way to define the evolution of the digital twin. Madni, Madni, and Lucero (2019) defines a digital twin based on its level of sophistication or maturity. Pre-digital twin, digital twin, adaptive digital twin, and intelligent digital twin does all adapt to different levels of maturity, as can be seen in Figure 2.4. Each of the four levels implies a specific purpose and can be used for decision-making (Madni et al., 2019).

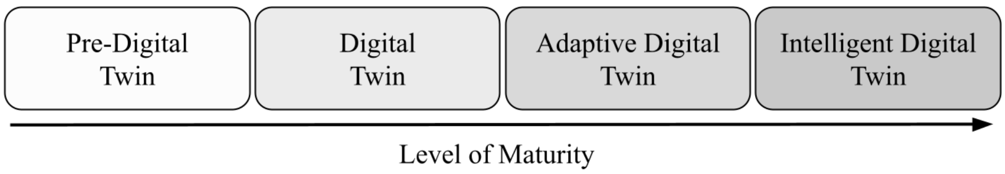

Figure 2.4: The digital twin defined by its four maturity levels.

The primary purpose of a pre-digital twin is to detect risks and identify issues with a design before the physical prototype is built (Madni et al., 2019). The pre-digital twin does not have a physical counterpart as the digital twin (Madni et al., 2019). With a higher level of maturity, the digital twin can incorporate data from its physical twin to support decision-making (Madni et al., 2019). The digital twin can be used to test different scenarios and explore how the physical model would act (Madni et al., 2019).

An adaptive digital twin has an even higher level of maturity and is offering an adaptive user interface (Madni et al., 2019). The user interface can then learn the preferences and priorities of the user depending on the context (Madni et al., 2019). The data is collected from the physical model in real-time and can be used to support real-time decision-making (Madni et al., 2019). The intelligent digital twin is the digital twin with the highest level of maturity (Madni et al., 2019). In addition to the capabilities that the adaptive digital twin includes, the intelligent digital twin also involves unsupervised machine learning and a high degree of autonomy (Madni et al., 2019).

Life Cycle

The life cycle of the digital twin can be divided into four phases, illustrated in Figure 2.5, freely redrawn from Hehenberger and Bradley (2016). In the design phase, the high-level requirements and experience from former developments are used to create the first design of the product or system (Hehenberger & Bradley, 2016). The foundation of the digital twin is then generated based on that design (Hehenberger & Bradley, 2016). The engineering phase includes additional engineering data like simulation models (Hehenberger & Bradley, 2016). The digital twin then works as a common archive where all the digital models created are saved (Hehenberger & Bradley, 2016).

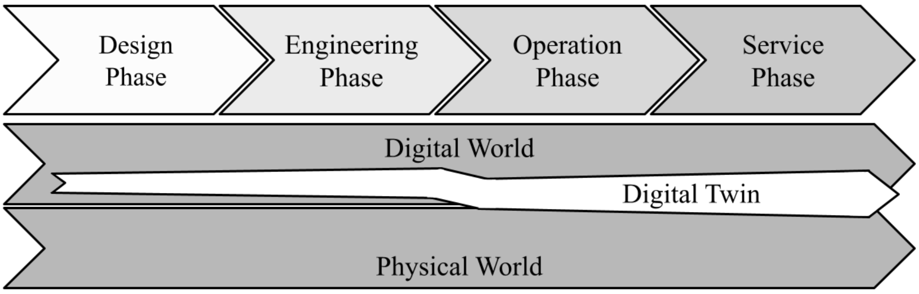

Figure 2.5: Evolution of the digital twin along the four life cycle phases. (Freely redrawn)

In the operation phase, the digital twin can be used for online condition monitoring of the product or system (Hehenberger & Bradley, 2016). The information from the design and engineering phase can be evaluated during the operation of the product or system (Hehenberger & Bradley, 2016). Data can be collected from the operation and hereafter used to verify and update the existing models (Hehenberger & Bradley, 2016). The knowledge gained from the verification and update can then be used to improve future products or systems (Hehenberger & Bradley, 2016). The service phase is the last in the life cycle before the loop is closed and restarted in the design phase (Hehenberger & Bradley, 2016). With the information gained from the earlier life cycle phases, the expected lifetime of parts or the fulfillment of design criteria can be deduced in the service phase (Hehenberger & Bradley, 2016). Flexible service planning is also enabled by using the data provided from the online measuring, simulation models, and operation history (Hehenberger & Bradley, 2016).

2.3 Technologies for Register Inventory Levels

In this section different technologies that can be used to register inventory levels are presented. There are numerous technologies available on the market that can be used to register inventory levels. Focus in this section will be barcodes, RFID, and several sensors, as visible in Figure 2.6.

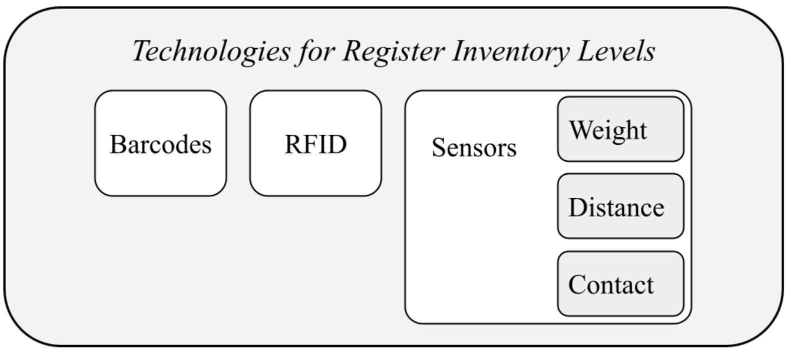

Figure 2.6: Technologies used for register inventory levels, described in the following sections.

2.3.1 Barcodes

Barcodes are a type of auto-ID technology, which refers to technologies that are used as an aid for machines to automatically identify and locate physical objects (Khattab, Jeddi, Amini, & Bayoumi, 2017; Wyld, 2006). The one-dimensional barcode is built up of lines with different thickness and space between, representing a binary code which gives basic information such as manufacturer and product (Khattab et al., 2017; L. Xu, Kamat, & Menassa, 2018; Wyld, 2006). To identify an article with one-dimensional barcodes, the codes have to be scanned with optical laser or imaging technology, in a certain position (Bashir, Naik, & Madhavaiah, 2013; Wyld, 2006).

Quick Response (QR) codes, are also a type of barcodes but are two-dimensional, consisting of squares instead of lines (L. Xu et al., 2018). These are able to store up to 7,089 characters, compared to the one-dimensionals' 20 (Bashir et al., 2013). QR-codes are designed with three-position detection patterns in the corners, making them possible to scan from any position (Bashir et al., 2013). Scanning is done by a device with a camera and software that can decode the data, such as a mobile phone (Bashir et al., 2013).

In the industry, barcodes are widely used for automatic identification of items (Khattab et al., 2017). For example, to keep track of what goods that are coming in, being stored, and leaving the warehouse (Hong-ying, 2009). By scanning incoming goods it is possible for workers to, without manual entering of characters, see if the goods match the order, and confirm if it does (Hong-ying, 2009). Data can also be saved of where the goods are being stored, as the storage space can have a barcode itself (Hong-ying, 2009). The scanning devices are then also used when picking goods out from the storage (Hong-ying, 2009).

By letting scanning devices translate codes into the warehouse management system, a lot of time is saved for the workers handling the logistics and also the risk of errors, such as faulty registered incoming goods, is reduced (Hong-ying, 2009). Barcodes are also simple, cheap, and universal (Khattab et al., 2017). However, they need a free line of sight to the scanning device, and could easily be unreadable in too dirty or wet environments (Khattab et al., 2017).

2.3.2 RFID

RFID is a technology used to store data and information related to an item (Khattab et al., 2017). By utilizing cheap wireless transponders, such as chips or tags, the technology can communicate the data and information without any direct contact (Khattab et al., 2017). An RFID transceiver provides an electromagnetic field that can interrogate the transponder and extract the stored data and information (Khattab et al., 2017). The RFID transceiver can both receive and transmit radio waves, unlike the transponder, which only can transmit radio waves depending on the waves from the transceiver (Khanna & Kaur, 2020). The transceiver, in turn, will then communicate with a software application on a back-end server, enabling an interface for the user (Khattab et al., 2017). An RFID transponder can operate at different frequency ranges, and each range brings its own benefits and thereby preferred application areas (Wyld, 2006). Four ranges are typically used for transponders; low, high, ultra-high, and microwaves (Wyld, 2006). The read range and reading speed are two of the parameters affected by the frequency (Wyld, 2006). A higher frequency entails a longer read range and faster reading speed (Wyld, 2006).

The RFID is one of the technologies that can be categorized as an auto-ID technology (Wyld, 2006). One of the most popular areas of application for RFID is within logistics and SCM (Khattab et al., 2017). With an RFID transponder attached to each item, they can easily be tracked, located, and identified (Kaur, Sandhu, Mohan, & Sandhu, 2011), and the technology can thereby provide inventory visibility (Khattab et al., 2017).

One of the main benefits of RFID, compared to barcodes, is that it does not require free line of sight when read, and the information on the transponder can be updated from a distance (Wyld, 2006). With RFID, human interaction can be reduced, hence, diminishing the risk of human error and decreasing the number of employees needed (Kaur et al., 2011). One RFID transceiver can read multiple transponders simultaneously, and the transponders are also suitable to use if the application environment is harsh and dirty (Wyld, 2006).

Besides the benefits, there are several challenges that RFID faces. For companies to be able to share the RFID application with other companies, standardization of communication protocols, and the format and amount of information saved on the transponder must be established (Kaur et al., 2011). While reading several transponders at the same time, a signal collision can occur (Kaur et al., 2011). At a cost, anti-collision algorithms can be used to prevent collisions (Kaur et al., 2011). Depending on which frequency the RFID transponder operates on, the data transmission can be corrupt by absorption or reflection of the signal due to ambient conductive materials (Kaur et al., 2011). Materials that can act conductive are, for example, containers with water or surfaces of metal (Kaur et al., 2011). Another challenge that must be taken into consideration is if the information on the transponders must be encrypted, preventing unauthorized persons from obtaining the information (Kaur et al., 2011).

2.3.3 Sensors

Sensors are another technology that can be used to register inventory levels (Hossain, Hossain, & Grabher, 2020). The sensors can detect a signal and send it to the system (Tejesh & Neeraja, 2018). Compared to other techniques that estimate the available inventory by using existing data from, for example, scanned barcodes, sensors can be used to update inventory levels automatically (Hossain et al., 2020). The cost of such industrial IoT sensors has decreased to 30% of the cost in 2004 (Statista, 2021a) at the same time as the interest to invest in such sensors and IoT increases (Statista, 2021c).

There are many different types of sensors available on the market, and they all have different ways to trigger and register signals. There are two main differences in how the sensors transmit the signal to the system, either through wire or wireless (Kim & Tran-Dang, 2019). When using wire, the signals are sent in cables, and in wireless settings, the signals are sent using radio waves (Kim & Tran-Dang, 2019).

If using wireless sensors, it is possible to create a Wireless Sensor Network (WSN) (Batra, Verma, Kavita, & Alazab, 2020). The WSN brings the potential of automating operations within, for example, industry by utilizing IoT (Batra et al., 2020). WSN builds a system that enables humans or computers to interact with a surrounding environment (Kim & Tran-Dang, 2019). In a WSN system, several wireless sensor nodes cooperate and observe a phenomenon occurring in the area of interest (Patil & Chen, 2017; Singh & Soni, 2021). A sensor node is a smart sensor (McGrath, Scanaill, & Nafus, 2014) that can perform sensing, process data, and wirelessly communicate the data (Uchiyama, Takamure, Okuno, & Sato, 2021). Sensor nodes require a power supply, either by battery or cable, which in some situations can be tricky, especially if there is limited space available for the sensor node (Uchiyama et al., 2021).

Sensors that can be used to track or count inventory are, for example, weight sensors, distance sensors, and contact sensors. The technology of the sensors and how those sensors can be used are presented in the following paragraphs.

Weight Sensor

One way to track and count inventory is by using a sensor that can generate a signal, that can be converted into weight. A strain gauge is one of the most common mechanical sensors, and the generated signal is based on the change of resistance (McGrath et al., 2014). The resistance measured is a result due to strain on one or a combination of several materials (McGrath et al., 2014). A Wheatstone bridge is normally used as the measurement circuit (McGrath et al., 2014). When the strain gauge is exposed to stress, the change in resistance will unbalance the Wheatstone bridge, which then generates an output signal (McGrath et al., 2014). A system including a strain gauge and bridge resistors is called a load cell (McGrath et al., 2014), see Figure 2.7.

A load cell is a transducer that transfers pressure to an electrical signal, proportional to the pressure applied (Kodali, Tirumala Devi, & Rajanarayanan, 2019). In other words, the load cell converts an analog signal to a digital signal using a Wheatstone bridge (McGrath et al., 2014). The output signal from the load cell is often in millivolt, and to amplify the small signal, an amplifier is needed (Kodali et al., 2019). HX711 is an amplifier that can be used in combination with load cells to register weight (Kodali et al., 2019).

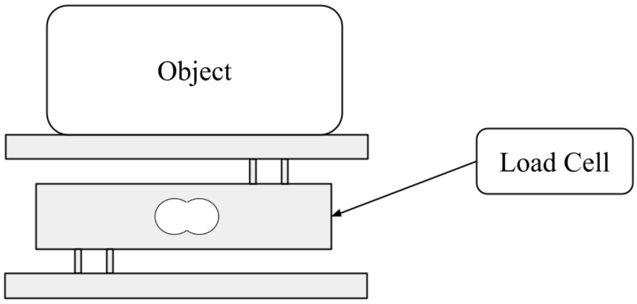

Figure 2.7: Schematic sketch of a load cell setup used to measure weight.

Distance Sensor

Another way to track, and in some situations count, inventory is by measuring the distance between objects. Ultrasonic Distance Sensors (UDS) can be used to measure distance (Dai, Zhao, Jia, & Chen, 2013) without having any physical contact with the object. The UDS use a pulse-echo sensor, which both transmits and receives signals (Dai et al., 2013). The sensor transmits a pulse, and the receiver detects when the pulse returns (Dai et al., 2013), see Figure 2.8. It is then the time between the transmitting and return of the pulse that creates the echo (Dai et al., 2013). The echo can be used to calculate the distance (Dai et al., 2013; Tejesh & Neeraja, 2018). Depending on the frequency used for the pulse, the measuring range and resolution for UDS differ (Frenzel, 2018). For example, with an HC-SR04 UDS, the measuring range provided is from 2 cm to 10 m (Adarsh, Kaleemuddin, Bose, & Ramachandran, 2016), with a resolution accuracy of 3 mm (SparkFun Electronics, 2021).

Infrared light (IR) is another technology used to measure distance (Adarsh et al., 2016). Just as the UDS, the IR sensor consists of both a transmitter and a receiver, see Figure 2.8. An IR LED emits a specific light of a wavelength in the IR spectrum (Adarsh et al., 2016). By analyzing the change in intensity of the received light, the distance can be measured (Adarsh et al., 2016). An IR sensor has a relatively short detection range (McGrath et al., 2014); for example, a SHARP GP2Y0A21YKOF IR sensor has a measuring range from 10 cm to 80 cm (Adarsh et al., 2016). One of the disadvantages of an IR sensor is that the color of the surface that the light is interfacing with (Adarsh et al., 2016), sunlight, fog, rain, and dust, can affect the reading of the sensor (McGrath et al., 2014).

A laser sensor is a third type of sensor used to measure the distance to an object (Konolige, Augenbraun, Donaldson, Fiebig, & Shah, 2008). Similar to the UDS and IR sensor, the laser sensor transmits a signal towards an object and then measures the signal received (Spitzer, 2006), see Figure 2.8. The signal transmitted is a laser beam, and by measuring the time it takes for the beam to travel to the object and back, the distance can be calculated (Spitzer, 2006). One of the main drawbacks with laser sensors is that it requires a higher cost compared to similar technologies on the market (Konolige et al., 2008).

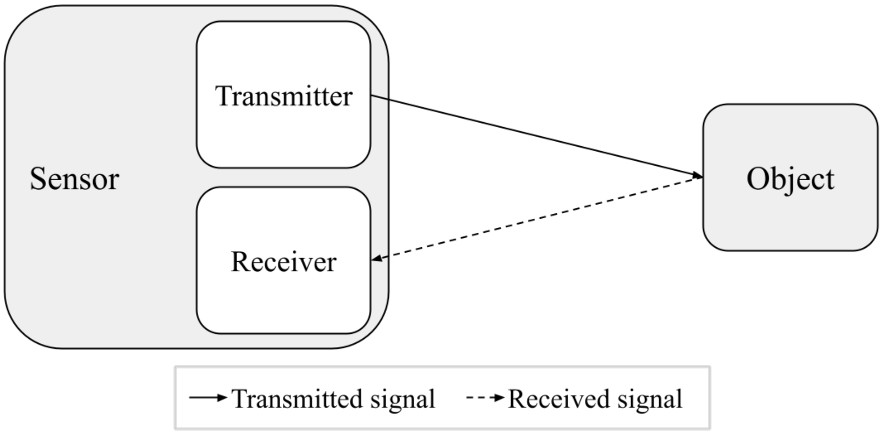

Figure 2.8: The principal function of a distance sensor.

Contact Sensor

Contact and contactless sensors can be used to check if an objective is in position or not (Nyce, 2016) and thereby count the available inventory on hand. A contact sensor has a physical part that moves when it comes in contact with the object (Nyce, 2016). When the physical part moves, it comes in contact with the stationary part of the sensor and generates an electrical signal (Nyce, 2016). In a contactless sensor, the moving and the stationary part of the sensor never make any physical contact (Nyce, 2016).

One type of contact sensor commonly used to track if doors or windows are open or closed is magnetic sensors (McGrath et al., 2014; Ransing & Rajput, 2015). A magnetic sensor consists of a magnet, which is mounted on the door or window, and a switch with terminals, which is mounted on the frame (ITWatchDogs, 2010). The switch connects signals from the wires and sends signals to the software when the distance between the magnet and the switch increases, indicating that the door or window is opened (ITWatchDogs, 2010).

2.4 Transmission of Data

In this section technologies that are used to transfer the data from the real world to the digital world is described. The data from barcode scanners, RFID transceivers, and sensors can be transmitted and used in different ways depending on the situation (Batra et al., 2020; Misra & Goswami, 2017). There are several ways to construct such connections. IoT can be used to connect devices with the Internet, and by that, be able to access the data from anything anywhere at any time (Borgia, 2014; Kashyap, Sharma, & Gupta, 2018). There are numerous ways to define how the physical devices interacts with the digital world. However, Borgia (2014) divides it into three phases called the collection phase, transmission phase, and process, management, and utilization phase. These three phases are visible in Figure 2.9 and described more in detail in the following paragraphs.

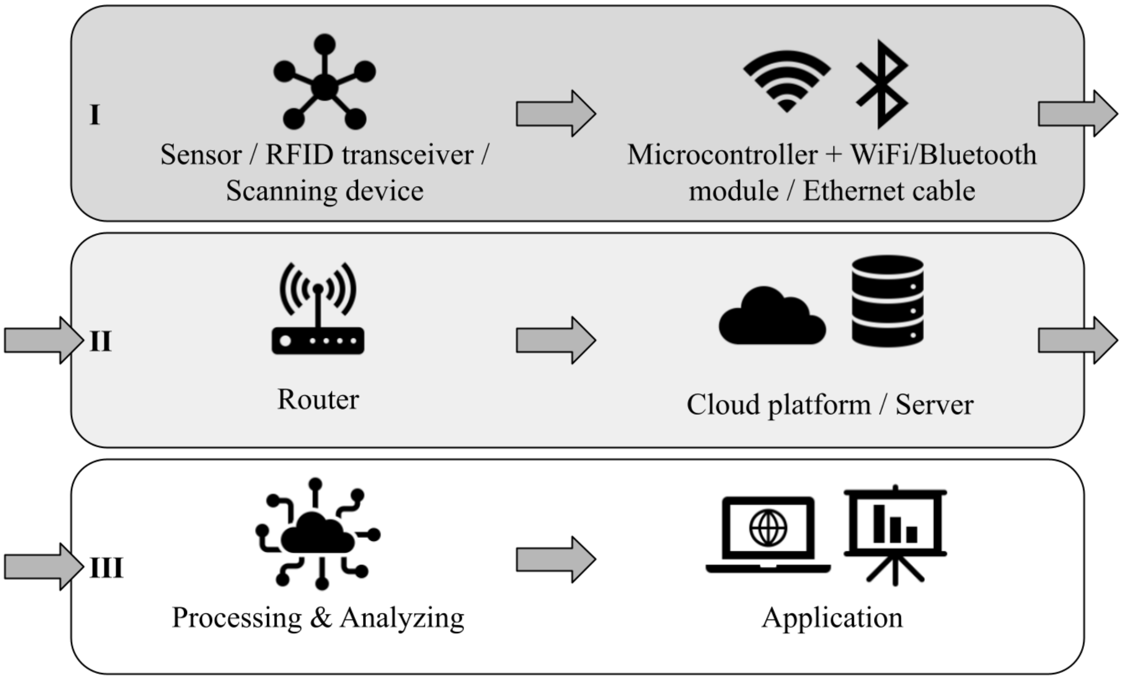

Figure 2.9: The three phases data can travel through between the real and digital world. Beginning with the collection phase (I), through the transmission phase (II), and ending with the process, management, and utilization phase (III).

In the first phase the data is collected from the real world through, for example, RFID transceivers and sensors (Abdel-basset, Manogaran, & Mohamed, 2018; Borgia, 2014). The transceivers and sensors can be connected into a WSN, and be called nodes (Tejesh & Neeraja, 2018). A microcontroller can be connected to the sensor or RFID transceiver. An example of such microcontroller to use is the ESP8266 (Tejesh & Neeraja, 2018), which is a sort of microcontroller with a WiFi-module attached and widely used in IoT applications (Hoddie & Prader, 2020). The microcontroller can be programmed, with for example Arduino IDE, to read certain data (Tejesh & Neeraja, 2018). Arduino IDE is an open-source Arduino software, which can be used to program different boards (Arduino, 2021). Some of the ESP8266 microcontrollers, like NodeMcu ESP8266 and Wemos D1 mini have a micro-USB socket which can be used for programming (Tejesh & Neeraja, 2018; Wemos.cc, 2019).

In the second phase, the data is delivered to the desired platform or server (Borgia, 2014). This can be done by wired technologies, where the standard is Ethernet (IEEE 802.3), which is relatively reliable and robust (Borgia, 2014). However, a more flexible solution is to connect the devices wirelessly, by, for example, Wireless Local Area Networks (WLAN) technologies such as WiFi (Borgia, 2014). With the attached WiFi-module to the microcontroller, described previously, it is possible to connect the microcontroller to the common WiFi with help of a router and send data wirelessly. The microcontroller can be programmed to operate as a station or as an access point, depending on the situation (Tejesh & Neeraja, 2018). The data can be transmitted through a gateway, switch, or router to a local server (Misra &

Goswami, 2017) or to a cloudbased platform on the Internet, which often is used for IoT applications (Borgia, 2014). To increase the efficiency and reliability between the node and application, a publisher and subscriber-based communication protocol, such as Message Queue Telemetry Transport (MQTT), can be used (Borgia, 2014; Gilchrist, 2016). MQTT makes the node (publisher) and server or application (subscriber) independent of each other, and constant connectivity between the both not required (Gilchrist, 2016). Messages logged while not connected will be stored and forwarded when possible by an MQTT broker (Gilchrist, 2016).

In the last phase, the data is processed and analyzed, and sent to other applications and services (Borgia, 2014). The data from the nodes needs to be processed and analyzed as it might look different because of various hardware and data formats (Borgia, 2014). For this, IoT platforms such as ThingSpeak can be used (The MathWorks, 2021). The gathered data can then be sent and visualized in different applications. One such is Mevisio, which offers a digital platform to share and visualize data streams within a whole organization (Mevisio, 2021b).

2.5 Visualization of Data

Raw data generated by WSN can be extensive and hard to grasp. To explore and gain insight from data, visualizations can be made (Toasa, Maximiano, Reis, & Guevara, 2018). Dashboards are widely used sources for visualization of data (Toasa et al., 2018). However, there are several ways to visualize the data also in the dashboard, and certain requirements of the system exists.

Park, Bellamy, and Basole (2016) summarize three requirements of such system. One is to support an interface with multiple and complementary views (Park et al., 2016). This because better-informed decisions can be made if several representations are possible to see, even if it is the same data used for both of these (Park et al., 2016). The other one is to enable interaction with the data, such as clicking, dragging, hovering, and filtering, and thereby be able to choose when to see certain detailed data (Park et al., 2016). The last one is to provide analyses and predictions (Park et al., 2016).

Toasa et al. (2018) describe several visualization techniques, used for exploratory data analysis. These are autocharting, correlation matrix, network diagram, Sankey diagram, and word cloud (Toasa et al., 2018). Autocharts can produce charts by drag-and-drop of data, and make, for example, bar charts (Toasa et al., 2018). Other types of charts are line charts and pie charts which often are used for visualizing trends respectively show proportions (Toasa et al., 2018). Numerous platforms are available to create visualizations, both manually and automatically (Toasa et al., 2018). Some of the most popular are Google Analytics, SAS Visual Analytics, Sisense, Tableau, and Zoho Reports (Toasa et al., 2018). There are also platforms less known, such as Mevisio's platform which is used for data visualization and collaborative work (Mevisio, 2021a).

2.6 Market Analysis

As a final part of the chapter, some developed concepts which are already on the market and using previously described technologies are presented. In the area of monitoring inventory levels of, especially C-parts, several concepts were found, and some of them work similarly. However, four of the identified concepts on the market will be described further. Each of the concepts presented uses different technologies or combinations of technologies to register inventory levels. The concepts also use data from the technologies differently.

2.6.1 Ambos.io - Storage Tower

The Storage Tower, presented to the right in Figure 2.10, is a storage system able to show real-time data of inventory levels and guide operators with pick-by-light (Ambos.io, n.d.). It is build up of one up to six modular rotating round discs stacked on each other, with each disc having slots for storing nine or 18 boxes, depending on the size of the boxes (Ambos.io, n.d.). Each disc have one slot with an integrated weight sensor and scanner, seen to the left in Figure 2.10 (Ambos.io, n.d.). The scanner is used to read barcodes on the boxes to keep track of which article is placed on each slot. The weight sensors are used to keep track of each article's quantity. The data is visualized in an application, which also can help the refilling- and reordering-process.

To mention some of the available technical specifications, the load is limited to be 100 kg on each disc, and the system requires a 230 V power connection as well as Ethernet or WLAN connection to be able to work (Ambos.io, n.d.). The cost for the hardware is €185 per storage space and for the software €1,990, plus a yearly fee of €960 (N. Krehmer, personal communication, March 8, 2021).

Figure 2.10: The Storage Tower provided by Ambos.io. Reprinted from *Storage Tower: The Smart Storage System*, in Ambos.io. Retrieved April 26, 2021, from `https://ambos.io/en/produkt/storagetower`. Copyright 2021 by Ambos.io. Reprinted with permission.

2.6.2 Bufab - Logistics Solutions Made Easy

Bufab has created several solutions that intend to smoothen the C-part management, which they call Logistics Solutions Made Easy (Bufab, 2021f). It consists of seven solutions: EasyTrack, EasyScale, EasyStack, EasyDrop, EasyScan, EasyVend, and EDI (Bufab, 2021f), and some of them are described below. All of the solutions build on standardized bins with unique QR-codes.

EasyTrack is a software application that can be used together with the other solutions, making it possible to monitor the levels, follow orders and do refilling of articles trough laptops, smartphones and hand scanners (Bufab, 2021e). The EasyScale concept consists of a scale in combination with a bin and keeps track of inventory levels, and can generate orders automatically when replenishment is needed (Bufab, 2021b). The EasyStack concept consists of a rubber mat where empty bins can be placed, as seen in Figure 2.11 (Bufab, 2021d). An antenna is built-in in the mat and sends a signal that refilling is needed when a bin is placed on the mat (Bufab, 2021d).

Figure 2.11: The EasyStack provided by Bufab. Reprinted from *EasyStack*, in Bufab. Retrieved April 26, 2021, from `https://www.bufab.com/services/global-part-productivity/logistics-solutions-made-easy/easystack`. Copyright 2021 by Bufab. Reprinted with permission.

EasyDrop is a solution for refilling of bins by dropping empty bins in a big collecting bin (Bufab, 2021a). The bins' QR-codes is interpreted by a reader in the collecting bin and an order is sent to Bufab (Bufab, 2021a). EasyScan is a concept of manual scanning of the bins' QR-codes when bins are empty (Bufab, 2021c). An order is generated directly in the scanning device and can be sent to Bufab (Bufab, 2021c).

2.6.3 Würth - ORSY

Würth has developed a storage management system called ORSY, which is a shortening of ORder with SYstem and consists of several products that can work together or by its own (Würth Industrie Service GmbH & Co. KG, 2021b). Some of the products will be described in the following paragraph.

ORSY Scan is an ordering system, used by scanning barcodes of articles in need of being ordered (Adolf Würth GmbH & Co. KG, n.d.). The laser scanning device is then read out at a computer and an order is created (Adolf Würth GmbH & Co. KG, n.d.). The ORSY Push is a combined ordering and storage system, that uses laser sensor technology to conclude when reordering is needed and creates an order (Würth Industrie Service GmbH & Co. KG, 2021a). It works with both flow racks and shelves together with cardboard boxes and bins (Würth Industrie Service GmbH & Co. KG, 2021a).

2.6.4 Neoalto - Automatic Ordering

Neoalto has developed a concept called Automatic Ordering, which suits the management of C-parts stored on shelves with a push feed system (Neoalto, n.d.). At the back of the shelf, a laser sensor is measuring the distance to the pusher and thereby determining the number of products left (Neoalto, n.d.). Automatic reordering is possible, as the sensor sends data in real-time to Neoalto's cloud, where reordering levels are determined (Neoalto, n.d.). In Figure 2.12, the real-world push feed system is presented to the left and its corresponding digital system to the right.

A case study done by Neoalto proves that by comparing the same system with and without Automatic Ordering, the number of deliveries can be halved, and the manual order handling is eliminated, which, in turn, leads to monthly savings (Neoalto, n.d.). However, the monthly cost of the service per stock keeping unit is €2.50 and per location is €13 (Neoalto, n.d.).

Figure 2.12: The Automatic Ordering provided by Neoalto. Reprinted from *Case Study: Automatic Ordering*, in Neoalto. Retrieved April 26, 2021, from `https://www.neoalto.com/solutions/automatic-ordering-case-study/`. Copyright 2021 by Neoalto GmbH. Reprinted with permission.

3
Methodology

It is important to consider the type of research question used when determining the method for the research (Yin, 2009). A combination of different qualitative and quantitative methods was therefore used to find answers to the research questions described in Section 1.4. Based on the research questions, the project was divided into the four following parts: Data collection, Mapping of Technologies and Requirements, Concept Creation, and Concept Integration and Visualization, as seen in Figure 3.1.

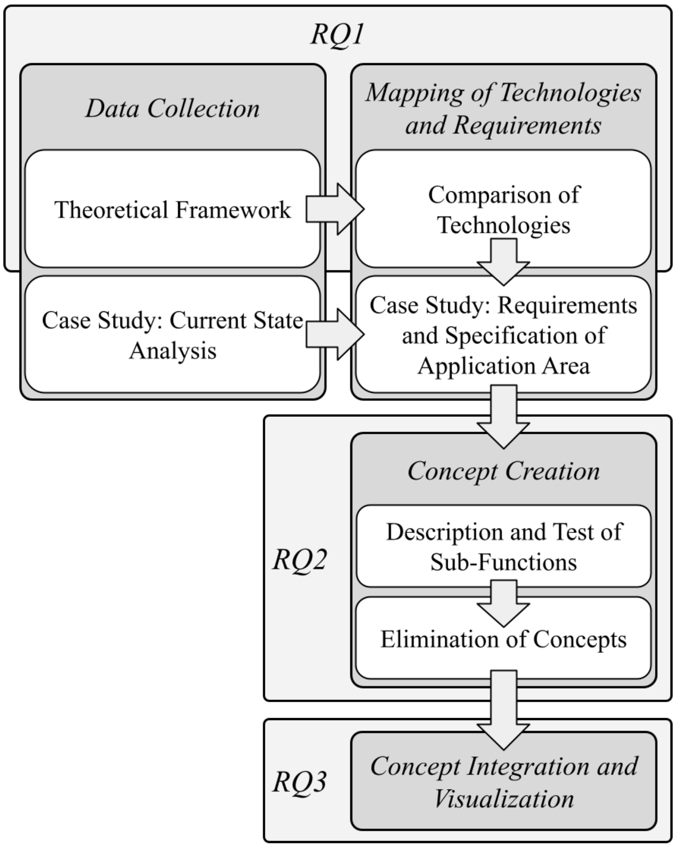

Figure 3.1: The main parts of the project and which research question each part aims to answer.

3.1 Data Collection

An essential element of problem-solving is the data collection (Pahl, Beitz, Feldhusen, & Grote, 2007). To reach the aim of the project, the data collection was divided into two parts, the Theoretical Framework and the current state analysis of the case. The Theoretical Framework was made to broaden the knowledge and understanding within inventory management, Industry 4.0, and different technologies that could be used, or are in use, to control inventory levels. The case study is used to provide a detailed description of a problem (Phillips & Stawarski, 2008).

Different methods were used within the data collection. In the Theoretical Framework and the current state analysis of the case, interviews were used. In both parts, these were unstructured, to encourage the interviewee to focus on the topics they think are significant or prominent (Mann, 2016).

3.1.1 Theoretical Framework

The method used to collect data for the Theoretical Framework was a triangulation of sources, presented in Figure 3.2. A literature search, statistics, and scoping of the market were the three sources used. A triangulation of various data sources, also called multi-method research, is used to increase the results' reliability (Jonker & Pennink, 2009). The result from the Theoretical Framework was used to answer RQ1.

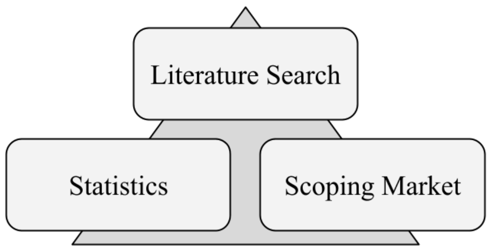

Figure 3.2: A triangulation of data sources used in the Theoretical Framework.

Literature Search

The literature search aimed to broaden the knowledge and understanding within two areas, inventory management and Industry 4.0. The background knowledge includes different concepts and terms used within the two areas. Relevant sources were found using keywords and related phrases on databases provided by Chalmers Library and Google Scholar. The databases mainly used were *IEEE, ScienceDirect, Scopus*, and *SpringerLink*. Different, and combinations of the keywords, were used to find sources for each area. Keywords mainly used for inventory management were, *C-parts, ERP, inaccuracies, inventory, inventory management, monitor*, and *supply chain management*. To find sources relevant to Industry 4.0, keywords like *BDA, cloud computing technologies, CPS, digital transformation, digital twin, Industry 4.0, IoT*, and *smart manufacturing* were used. The sources found were also used to identify relevant cited sources within the same topic.

Statistics

In addition to the literature search, parts of the data collection were reinforced with statistical data from Statista. Chalmers Library recommends Statista as it is a database with statistics from market and opinion research institutions and, also, from business organizations and government institutions (Chalmers Library, 2021). To find relevant data, the keywords *data, IoT, sensors*, and *supply chain*, were used.

Scoping Market

An initial market analysis was performed to find relevant technologies on the market. Information about the technologies found was further extracted from an additional literature search on databases previously presented. The keywords and combinations of keywords used to find relevant literature were, *barcode, contact, data visualization, IR, IoT architecture, load cell, network architecture, network structure, RFID, sensors, ultrasonic*, and *WSN*. Information from company-websites about technologies used by specific companies were also included in this part of the data collection.

A market analysis was performed to identify similar concepts on the market. Secondary sources, like company-websites, were used to provide information about the concepts. Primary sources in terms of interviews and email conversations with companies and people that have been involved in similar projects were also conducted to gain supplementary information.

3.1.2 Case Study: Current State Analysis

The current state analysis of the case is the second part of the data collection. The case study was conducted at Virtual Manufacturing's assembly site in Linköping. The case is an example of where the physical and logical inventory of C-parts does not match and thereby causing problems.

As Neale, Thapa, and Boyce (2006) propose, the study began with a problem identification and explanation of why it should be solved. To achieve an as complete picture as possible of the problem this was done by collecting data from several methods (Neale et al., 2006) namely, interviews, internal documents, and on-site observations. Unstructured interviews were conducted with the purchaser in Gothenburg and employees at the assembly site in Linköping to get an initial perception of the situation. The interviewees' thoughts of why the problems occur and how they would like to change the assembly site to prevent problems were also covered in the interviews. Internal documents of the fasteners in use were reviewed to gain knowledge about, for example, quantity, annual consumption, and order volume.

To get to know the organization and the problem objectively, an open observation was conducted (Jonker & Pennink, 2009) at the assembly site in Linköping for two days. It consisted of direct observations and participant observations of events related to the processes of ordering, refilling of material, assembly, and disassembly. Notes were taken during the two days to ensure that details were considered. A first draft of the current state analysis was written, and later evaluated by one of the employees. The evaluation was mainly conducted to ensure that the observations were aligned with reality. Notes from the evaluation were taken into account when the final result from the current state analysis was completed.

3.2 Mapping of Technologies and Requirements

The mapping consisted of three parts. Firstly, a comparison of technologies for registering inventory levels, evaluating the technologies against different criteria. Secondly, the requirements from the current state analysis of the case were identified. Lastly, a specification of the application area within the case study was made. The process of these three parts will be further described in the following paragraphs.

3.2.1 Comparison of Technologies

Findings from the Theoretical Framework were used to answer RQ1. These findings, together with the authors' knowledge gained during the project of the different technologies used for registering inventory levels, were compiled into a table with various criteria. The chosen criteria were based on how suitable the technologies would be to register inventory levels within the system investigated. For example, what the technology requires from the system it is applied on and what constraints and possibilities it brings.

3.2.2 Case Study: Requirements

Based on the current state analysis and the Comparison of Technologies, different potential requirements of demands and wishes emerged. The requirements were listed and presented to two employees at Virtual Manufacturing. Firstly to the purchaser and secondly to another employee who is well-versed within the area. During the selection process, the employees could add additional requirements or comments to the existing ones.

Demands

Questions were formulated to identify the demands from the case study. Each question had two or three possible alternatives from which the employees were to choose. Questions, and their associated alternatives, were discussed one at a time to ensure that the employees clearly understood the significance of the demand. When one alternative was selected for the question, it was marked, and the next question was introduced.

Wishes

As for the demands, a similar method was used to distinguish the wishes. The wishes from the case study were presented one at a time with its associated alternatives. Each alternative was given an internal rank, depending on what was considered to be of the highest priority. After all of the wishes and alternatives were reviewed and discussed, each of the wishes was ranked by importance. The final result was a table, similar to Table 3.1, with both the overall and internal rank of the wishes.

Table 3.1: Table template used to describe the result from the prioritization of wishes of the concept.

Overall Rank	Wish	Alternative and Internal Rank
1. *(Wish of highest importance)*	*(Description of Wish A)*	1. *(Alternative of highest importance)* 2. *(Alternative of second highest importance)* 3. *(Alternative of least importance)*
2. *(Wish of second highest importance)*	*(Description of Wish B)*	1. *(Alternative of highest importance)* 2. *(Alternative of least importance)*
...	...	...

3.2.3 Case Study: Specification of Application Area

Based on the demands and a discussion with the already involved employees at the company, it was possible to select which inventory to include when measuring the inventory levels. After this selection, another specification was required. It was concluded that the inventory system in use needed an adjustment before further development of any concept. The conclusion was drawn based on the Comparison of Technologies and the case study's current state analysis and requirements. The adjustment was to switch from the existing inventory system to another. It was primarily done to standardize the system on which the concept will be based. The switch was also done to make the system compatible with as many of the identified technologies for register inventory levels as possible. The standardization also improved the future possibility to apply the concept in other cases besides the investigated.

3.3 Concept Creation

In order to answer RQ2, concepts were generated. The first step in the concept creation phase was to map the function structure of the system to identify the subfunctions of the overall function (Pahl et al., 2007). Figure 3.3 shows a general example of a block diagram of a function structure. The solutions for each subfunction generate the working structure, which will lead to the principle solution (Pahl et al., 2007), the concept. The functional interrelationship between the inputs and outputs of the system is needed to be able to solve a technical problem (Pahl et al., 2007). The function structure is an approach traditionally used by engineers (Pahl et al., 2007).

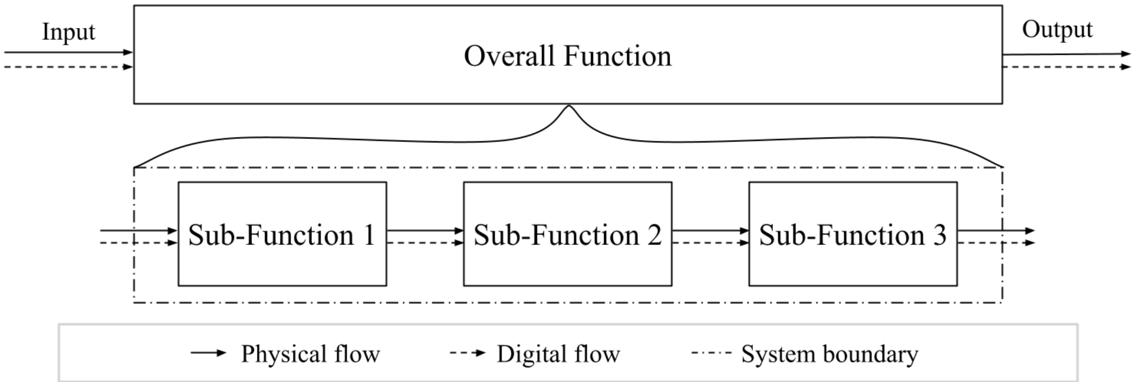

Figure 3.3: Relationship between the overall function and its serving sub-functions.

3.3.1 Description and Test of Sub-Functions

After the sub-functions were identified, the input, the sub-function itself, and the output from the sub-function were described. Different ways to solve these sub-functions within the specified application area were generated based on knowledge gained from the Theoretical Framework.

For Sub-Function 1, there was not enough information to decide if the solution would be appropriate or not in the investigated system. A test phase was performed to, firstly, ensure that only technologies suitable to use in the system investigated are included in the concept creation and, secondly, to examine certain functionalities. Depending on which technologies needed testing, they were purchased or borrowed. A mini-flow rack available at the company, seen in Figure 3.4, was used for the tests.

Figure 3.4: Pictures of the mini-flow rack where tests were performed. A gray object is placed in the mini-flow rack. The mini-flow rack is approximately 30 cm wide and deep. (Authors' images)

The uncertainties that were identified when generating solutions were examined in the test phase. The technology used for register inventory levels was mounted in the mini-flow rack in the position suitable for each particular case. Before the test was started, the technology was calibrated. Throughout the tests, one and two objects were placed in the mini-flow rack to evaluate if the technology could determine the number of objects. To do this, the technology was connected to a computer where the measured values were visible.

3.3.2 Elimination of Concepts

After generating solutions for each sub-function, different concepts were created. Different solutions for Sub-Function 1 were combined with an unspecified solution for Sub-Function 2 and 3 due to the focus of the project's aim. The concepts were further evaluated in an elimination matrix based on how they met certain elimination criteria. The criteria were based on the case study's demands. The concepts that did not meet the demands from the requirements list were eliminated, as proposed by Pahl et al. (2007). To further eliminate concepts with low potential, also the highest prioritized wish was included as a criterion. Concepts that were not eliminated were included in the next phase, the Concept Integration and Visualization.

3.4 Concept Integration and Visualization

In order to answer RQ3, prototypes of the concepts that were kept after the elimination matrix were integrated and evaluated in a test environment at Virtual Manufacturing's office in Gothenburg. The test environment consisted of Workstation One, which usually is used for testing and showing equipment to customers. As seen in Figure 3.5, Workstation One is designed with the same components as the mini-flow rack but in full scale, similar to the specified application area.

The physical prototypes of the concepts had the same setup as used in the tests of Sub-Function 1. However, the tasks performed by the microcontroller had to be expanded, to support remote monitoring of the inventory level. One of the alternative solutions was chosen for Sub-Function 2 respectively Sub-Function 3, with respect to software used at the company or accessible through student licences provided by Chalmers.

The prototypes were mounted and calibrated in Workstation One. An evaluation test then began to examine the precision of the concepts. This was examined by successively placing one, two, and three boxes in the flow rack, remove them one by one and verify that the output values correspond to the true number of boxes. The output values, together with the true number of boxes, were compiled in a graph. The boxes were placed and removed at an interval of 30 seconds. Observations, besides the precision, were noted as well. Remarks related to the microcontroller's behavior, which was considered possible to manage, were included in an iterative improvement process.

The remotely generated data were then visualized in a digital twin. One way to visualize the data was demonstrated in the digital twin used by the company. The graphs compiled were integrated, with the values updating in real-time. The visualization was presented to the company to get feedback and discuss further improvements.

Figure 3.5: Picture of Workstation One where the prototypes were integrated and tested. (Authors' image)

4
Results

Following the previously described methodology, this chapter describes the results obtained. It will be presented in chronological order, beginning with the findings from the current state analysis of the case study and the Comparison of Technologies. It is then followed by the case-related requirements and the Specification of Application Area. Lastly, the result from the Concept Creation and the Concept Integration and Visualization is presented.

4.1 Case Study: Current State Analysis

Virtual Manufacturing's assembly site in Linköping produces, among others, modular flow racks, trolleys, and workstations (Virtual Manufacturing AB, n.d.). The products are available both in standard and customer-specific versions. At the assembly site, the number of operators varies between two and five, depending on the current demand. One operator is responsible for the whole assembly of a product. Since many of the products are customer-specific, there is a high variation of the products. The layout of the site is designed after the processes to adapt to the high variation and relatively low production volumes.

In the following sections, the material storage and material flow at the assembly site are described. The reasons and consequences for material shortages are also included. Finally, a description of the company's digital twin, called the Virtual Twin, is presented.

4.1.1 Material Storage

The storage of material at the assembly site is not standardized for all materials at the site. One essential type of material used at the assembly site is different types of fasteners. The fasteners are placed in a tilt bin storage system with one bin for each type of fastener. Cardboard boxes and plastic bags with fasteners used to refill the tilt bins are placed on shelves and on the floor. These boxes and bags are considered to constitute the inventory buffer. The material storage area of the current state, including the inventory buffer, is presented in Figure 4.1.

The material in the inventory buffer is not assigned to a specific position on the shelves. To keep the material in order, it is placed approximately vertically under each tilt bin when space is available, but this is not strictly followed by everyone working at the assembly site. Above the tilt bin storage system, cardboard boxes with wrongly ordered fasteners are arranged, further described under Reasons in Section 4.1.3.

Figure 4.1: Picture of the material storage area of the current state. (Authors' image)

Other materials used at the assembly site are stored differently. The inventory buffer of joints is stored in flow racks, and the boxes from which the operators pick material are placed on shelves. This system is considered to work well according to the employees, although it requires manual stocktaking and does not ensure that the right box of material is placed at the assigned slot in the flow rack.

4.1.2 Material Flow

The flow of material can be divided into three parts, namely, consumption, stocktaking and ordering, and delivery and refilling. In the following paragraphs, the different parts are described in more detail.

Consumption

During assembling of products, operators follow a printed drawing based on a CAD-model and pick fasteners from the tilt bins. The drawing includes a BOM, presenting all the material required for the product. The operators put the fasteners they think will be needed for the assembly in a plastic box or their tool belt and bring it to the assembly station. If the operators collect fasteners not required for the assembly, they put the remaining material in its assigned tilt bins when the assembly is completed.

Stocktaking and Ordering

Orders can be based both on customer orders and weekly stocktaking, as seen in Figure 4.2. With previously mentioned BOM of the products, the purchaser can control the material needs in the ERP system, create an order, and ensure available material. The order is then considered to be based on the customer needs.

Every Thursday, one operator at the assembly site is responsible for refilling all the tilt bins with material from the inventory buffer. The day after, there is a weekly manual stocktaking done with visual inspection by one of the operators. The only parameter taken into account by that time is the amount of material in the tilt bins and the inventory buffer. The operator indicates the need for new purchases by calling the purchaser located at the office in Gothenburg. The purchaser notes type and quantity, place the order at the supplier, and register it in the ERP system.

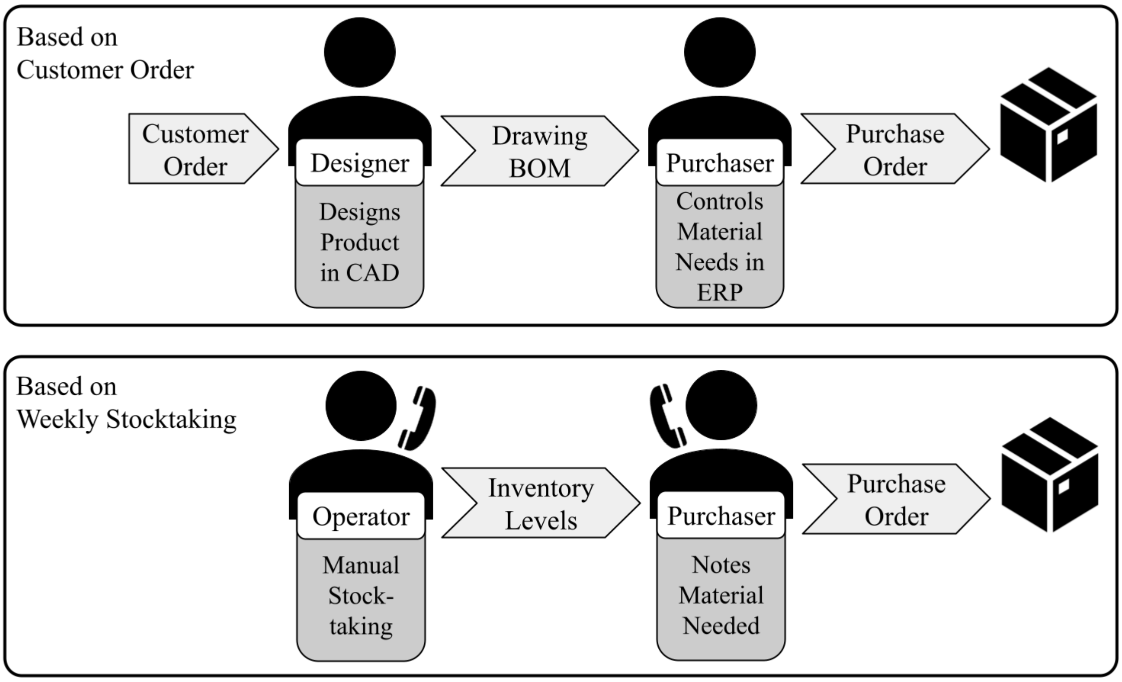

Figure 4.2: Overview of the part of the material flow describing the ordering of material, which can be based both on customer orders and weekly stocktaking.

Delivery and Refilling

Once orders are delivered to the assembly site, the order is placed on a shelf close to the delivery-gate. The incoming orders are not always double-checked and controlled. One worker brings the material to the material storage area when there is time left over. If there is space for the material in its assigned tilt bin, refilling is done directly, otherwise, it is put on the shelf below where there is space. If an article is incorrectly ordered, it is placed on top of the tilt bins. Refilling is not only done when the material is delivered from the supplier. When a tilt bin is empty, the workers refill it with material from the inventory buffer on the shelves below.

4.1.3 Material Shortages

There are different reasons for material shortages occurring at the assembly site. Depending on the situation, the consequences also differ. Some of the most prominent reasons and consequences will be further described below.

Reasons

There are different reasons why the required material sometimes is missing at the assembly site. For example, when the BOM is incomplete, more material is required than what is shown on the drawing. This means that the material-withdraw will increase, but this is not registered anywhere, resulting in an inaccurate stock balance in the ERP system. Sometimes the purchases are placed too late, which means that the demand during delivery lead time is higher than the safety stock. It could also be the case that the material supplier does not deliver as promised.

Another reason for material shortages is when wrong material is delivered to the site, and there are two perspectives to this. Either the supplier has sent the wrong articles, compared to what is actually ordered. Or, there has been some miscommunication or misunderstanding between the operator at the assembly site and the purchaser in Gothenburg, then the order itself is wrong. The main reason for wrong orders is that the system used is not standardized, which then allows for the wrong material to be ordered. In some cases, the material in the wrong order can still be used, but otherwise, the material is placed on the top shelf in the material storage area.

Deficient update of the inventory in the ERP system is another reason for material shortages. When production documentation is generated for a product, based on the CAD-model, the ERP system calculates the available stock on hand and indicates if a sufficient amount of material is available. With a deficient update of the inventory, the available stock on hand does not stand for the actual stock on hand, which gives inaccurate indications of the inventory levels.

As the inventory buffer is organized in the current state, the material is often disarrayed. In those situations, the ERP system can indicate that there will be material available, but the operator is not able to find it due to the disarray.

Consequences

When the required material is missing, the ways to solve the problem depend on the article and the urgency. When parts neither are interchangeable to something in stock nor can be awaited until re-stocked, last-minute purchases are necessary. A worker from the assembly site then drives and buys the material at a local re-seller in Linköping. Last-minute purchases occur several times a month, which takes time for the worker that otherwise could have been spent on assembly. According to the company, the personnel cost for one of these purchases is about 1,500 SEK.

4.1.4 Virtual Twin

Virtual Manufacturing has developed a concept of a digital twin called Virtual Twin. It has similar functionalities as a digital model, considering its level of integration. They use the concept both by themselves and sell it to their customers. Today the Virtual Twin could be used for several things, such as safety training, visitor tours, Gemba walks, and remote collaborative work. In daily work, the Virtual Twin is used for projects within, for example, simulation and layout changes. Considering the level of analytics, the Virtual Twin partly fulfills the first level, descriptive analytics.

To create a Virtual Twin of a factory, the process begins with a 3D-scanning of a selected area. Virtual Manufacturing performs the scanning with a NavVis M6, which creates a point cloud and map it together with photos in every direction. The scan is then imported to NavVis Indoorviewer, to be accessible via the Internet browser. The NavVis Indoorviewer looks similar to the more widely known Google Street View. In the Internet browser, it is possible to navigate between buildings and floors, take out measurements, see routing suggestions, and see a Point Of Interest (POI). A POI is visualized as a button with an icon describing the category in which it is assigned. When hovering over the POI, the name is also visible. When clicking on the button, additional information about the POI is seen. It is also possible to integrate other software into this Virtual Twin. Virtual Manufacturing uses a digital board for the management of their daily operations, called Mevisio. Information from Mevisio could therefore be visible when clicking a POI in the Virtual Twin.

In the future, there is a plan to also integrate other software into NavVis Indoorviewer, such as RS Production, which could show, for example, real-time machine statistics. Besides the integration of more software, there is a goal of integrating more data into existing software, such as inventory levels. There is also a vision to connect data from the Virtual Twin to the ERP system and the other way around.

4.2 Mapping of Technologies and Requirements

The mapping includes three parts, a comparison of the technologies for register inventory levels, the requirements identified from the case study, and the specified application area. The requirements consist of both demands and wishes, which are presented in two separate tables.

4.2.1 Comparison of Technologies

Criteria used to compare the identified technologies from Section 2.3 are prerequisites, suitability, uncertainty, pros, and cons. Prerequisites include what is needed from the system investigated for the technology to work. Suitability defines how well the technology is suitable for the investigated system. Uncertainty refers to the risks that can result in inaccurate data. Pros and cons describe the notable benefits and drawbacks of the technology. The result from the comparison is presented in Table 4.1 and is based on the Theoretical Framework and the authors' gained knowledge during the project.

Table 4.1: Comparison of technologies for register inventory levels.

Criteria	**Barcodes**	**RFID**
Prerequisites	Scanning device required. Well followed procedures of manual scanning. Barcodes on all cardboard boxes.	One transponder on each cardboard box/reusable bin. Transceiver required.
Suitability	Well established and used in similar systems.	Popular within logistics and SCM. Suitable for articles with higher purchasing cost.
Uncertainty	Faulty scans.	Collision of signals. Faulty labeling/refilling of cardboard box/reusable bin.
Pros	Simple. Cheap. Universal.	No physical contact required. Simultaneous reading of transponders possible.
Cons	Require free line of sight. Damaged barcodes are unreadable. Manual handling of incoming goods and empty boxes.	Metal surfaces can corrupt the signal. Manual handling of incoming goods (labeling/refilling of cardboard box/reusable bin).

	Weight Sensor	**Distance Sensor**	**Contact Sensor**
Prerequisites	Require calibration of each article. Each article must have an assigned place with one sensor.	Require calibration of each article. Each article must have an assigned place with one sensor.	Each article must have an assigned place with one sensor.
Suitability	Well used in horizontal positions (scales).	Laser sensor used in push-feed systems.	Well used to check if an object is there or not.
Uncertainty	Wrong placement of articles. Miscalibration. Temporary disturbances.	Wrong placement of articles. Miscalibration. Temporary disturbances.	Wrong placement of articles. Temporary disturbances.
Pros	High precision (number of pieces). No manual handling.	No physical contact required. No manual handling.	Simple. No manual handling.
Cons	Require handling/filtering of data. Require installation and calibration.	Require handling/filtering of data. Require installation and calibration. Require free line of sight.	Require handling/filtering of data. Low precision (no/any inventory). Require installation.

4.2.2 Case Study: Requirements

The demands and wishes chosen by the company are presented in Table 4.2, respectively Table 4.3. In Table 4.2, the five identified demands, covering different areas, are visible. The preferred alternative to each question is marked in bold.

Table 4.2: Alternatives of possible demands presented to the company. Preferred alternatives are marked in bold.

Demand	Alternative 1	Alternative 2	Alternative 3
Scope: Only avoid material shortages or also digitalize data from inventory levels?	Avoid material shortages	**Avoid material shortages and digitalize data**	
Frequency: How often should the inventory levels be updated?	Real-time (seconds or minutes)	**Daily**	Weekly
Precision: With what precision should the inventory levels be specified?	Empty or not	**Number of boxes**	Number of fasteners
Assembly handling: Is the handling process, at the assembly, changeable?	**Changeable**	Unchangeable	
Storage handling: Is the handling process, before the storage, changeable?	**Changeable**	Unchangeable	

There are nine wishes that the company wants to fulfill, presented in Table 4.3. Manual handling includes the time the operator at the assembly site spends on administrative tasks related to the inventory. System boundary defines which places the concept should involve, if it only should include the inventory at one place or at several positions in the area. Cost per article is what the concept will cost if the expenses are divided between all the articles. Packaging solution compatibility refers to if the concept should be possible to use with different packaging types of the articles or the same.

Remote monitoring is the wish of having a concept that is or is not dependant on a second party. Connection is the link between the registering of data and the application used to visualize the data. Packaging solution is in which type of packaging the articles should be displayed in the storage system, either the ones they are delivered in or if they should be refilled into reusable bins. Power source describes the wish of how the concept should be powered. Lastly, simplicity refers to if the installation and implementation are preferred to be simple.

Table 4.3: Prioritization of wishes of the concept presented to and ranked by the company. An empty cell means there were no alternatives to be internally ranked.

Overall Rank	Wish	Alternative and Internal Rank
1.	*Manual handling*	1. Avoid 2. Unchanged 3. Increased
2.	*System boundary*	1. Material at different locations 2. Material at one place
3.	*Cost per article*	
4.	*Packaging solution compatibility*	1. Same everywhere 2. Different packaging solutions
5.	*Remote monitoring*	1. Independent of others 2. Dependant of others
6.	*Connection*	1. 3G/4G/5G 2. WiFi, Bluetooth 3. Wired
7.	*Packaging solution*	1. Cardboard box (as delivered in) 2. Reusable bin
8.	*Power source*	1. Wireless, Battery 2. Cable
9.	*Simplicity*	

4.2.3 Case Study: Specification of Application Area

The focus of the storage system is decided to be on the inventory buffer, seen in Figure 4.1. The demand specifying the precision level was essential in this selection. The material in the tilt bins will thus not be taken into account when monitoring the inventory levels. The storage system for which the concept will be applicable, based on several reasons, are flow racks. One reason for the choice is that the company already uses flow racks when storing other material at the assembly site. Another reason is that a flow rack would fit into the same space as the now used shelves, and therefore layout changes at the assembly site would not be required. An example of a flow rack that would be possible to implement at the site, instead of the shelves, is presented in Figure 4.3.

From the Comparison of Technologies, the prerequisites imply that the technologies would not work in a storage system like the one described in the current state analysis. All sensor technologies presented in Table 4.1 require articles to be assigned to a specific place, which can be successfully done with flow racks. Barcodes and RFID do not need a flow rack but are still compatible with it.

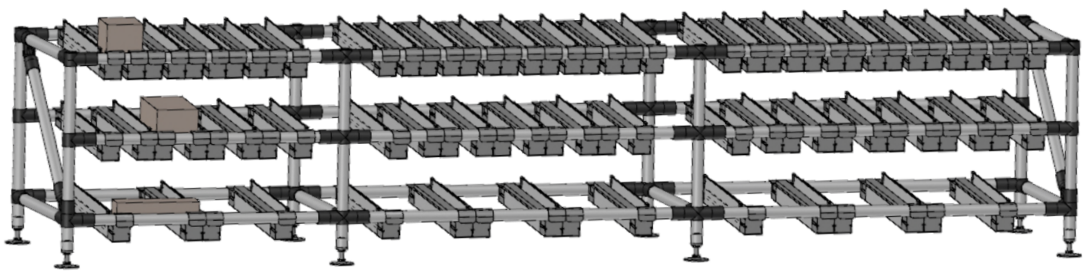

Figure 4.3: Flow rack that can be used for the inventory buffer. The three boxes represent the material that will be stored in the flow rack, which could have different dimensions.

4.3 Concept Creation

The overall function of the concept is to monitor inventory buffer levels, seen in Figure 4.4. The input to the overall function is the physical inventory levels, and the output is digital information of the inventory levels. Registration of inventory levels, transmission of data, and visualization of data are the three sub-functions identified, described in the following paragraphs. The concept creation phase ends with the elimination of concepts.

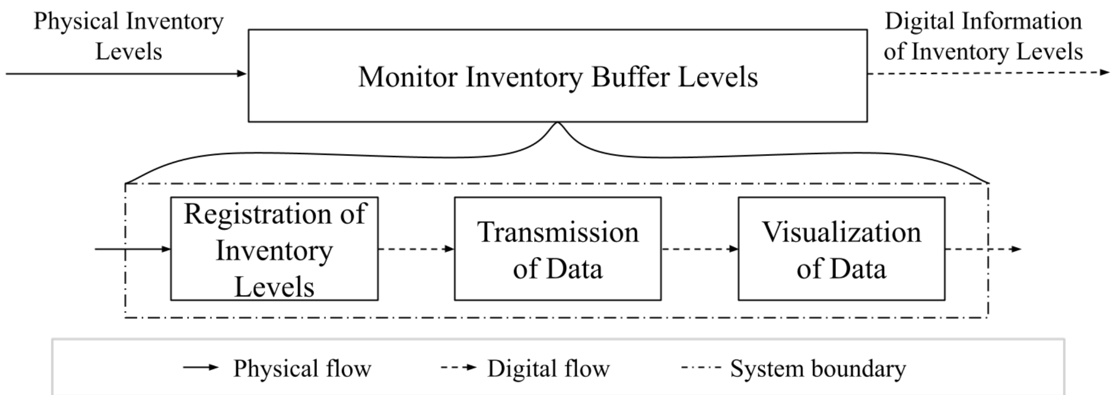

Figure 4.4: Functional structure of the concepts generated, based on the case study.

4.3.1 Sub-Function 1: Register Inventory Levels

The first sub-function's main purpose is to transform the physical inventory level to a digital signal. This entails that the technology used must intercept information about the levels of inventory in a flow rack and transform this physical state to a digital signal. From the Theoretical Framework and the Comparison of Technologies, the options to do this are with barcodes, RFID, weight sensors, distance sensors, and contact sensors. From Table 4.1, it is not clear how the technologies would work in a flow rack. In the following paragraphs, descriptions of how the technologies could work in such environment are described.

Barcodes

Both one- and two-dimensional barcodes would require a manual scanning procedure of the cardboard boxes. A routine would be required both to register incoming goods and to register when a cardboard box is used, for example, by registering when a box is emptied. The procedure could be applicable on a flow rack storage system, but the same type of article would always need the same information on the barcode. To ensure that this is fulfilled, the supplier should be standardized for each article. As seen in Table 4.1, barcodes are frequently and well used to control inventory. Using barcodes to register inventory levels in a flow rack are not considered to need performance tests.

RFID

When using RFID to register inventory levels, a transponder would be needed on each container. The container could either be the cardboard boxes in which the articles are delivered from the supplier or reused bins. Both alternatives would require manual handling when receiving articles from the supplier. One option is to attach a transponder to the cardboard boxes when they are received from the supplier. Another option is to fill reused bins that already have a transponder attached with material from the cardboard boxes.

The transceiver could be fixed on the flow rack and automatically scan containers or be in a handheld scanning device used by an operator. There are different ways to keep track of the containers, such as register the containers in the flow rack. Another way is to place the emptied containers by a place equipped with a transceiver that registers the empty containers.

As the transponder and receiver do not need any physical contact to communicate, the design of the storage system does not affect the performance of the technology. However, as described in Table 4.1, metal surfaces can corrupt signals, but there are existing solutions to prevent this problem. Using RFID to register inventory levels in a flow rack system is therefore not considered to need performance tests.

Weight Sensor

A weight sensor could be used to measure the weight of containers in a flow rack. For each article, the sensor is calibrated with one container. The value of one container is then used to calculate how many containers there are in the specific section of the flow rack. Using a weight sensor mounted in horizontal position, like in a kitchen scale, is widely used. However, in a flow rack there could be a possibility to mount the sensor at the front. The sensor, which can be a load cell, can then measure the force that the objects are pushing on the sensor, as seen in Figure 4.5. Neither setups with weight sensors mounted in flow racks, nor weight sensors used to measure horizontal forces, were found when compiling the Theoretical Framework. Using weight sensors to register inventory levels in a flow rack system is therefore considered to need performance tests to ensure that the technology can be used.

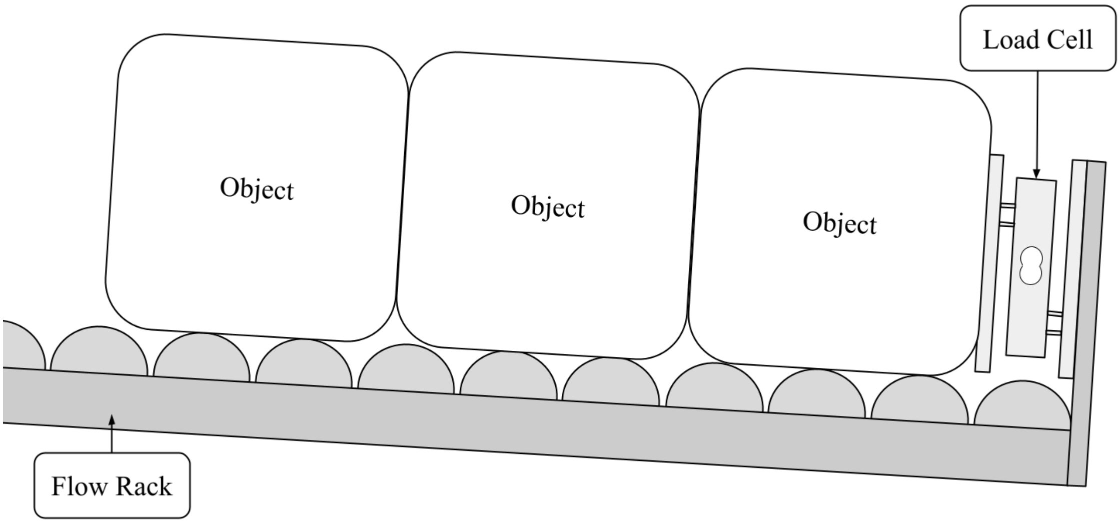

Figure 4.5: Illustration of a setup with the load cell in a flow rack.

The uncertainty tested is the weight sensor's ability to measure a force in non horizontal position, in a flow rack. The setup consisted of a load cell, with a capacity of 10 kg, attached to two wooden boards with bolts and nuts, as seen in Figure 4.6. The wires from the load cell are connected to an amplifier (HX711), which in turn is connected to a microcontroller (Wemos D1 mini). The microcontroller is connected by USB cable to a computer, where the software Arduino IDE is installed. The software is used to program the microcontroller and to monitor the output values. In Appendix A, the schematic illustration of the setup can be found.

From the test, it is observed that the values from the load cell fluctuate despite a constant number of boxes. Depending on the angle between the load cell and the object, the force applied to the load cell gets affected. Hence, when the angle is changed, so are the values from the load cell. Therefore, an identified issue is the mounting of the load cell. It is difficult to ensure the exact angle and to fixate it in that position, which causes the load cell to be sensitive to, for example, hits.

The material mounted on the load cell also affects the load cell, and thereby the output values. Another identified concern is how much space the load cell takes up. As it is mounted in front of the mini-flow rack, it can be in the way when picking objects. To ensure that it is possible to pick the objects, there must be enough free space above the objects and the load cell. Despite the mentioned issues, it is possible to, with the measurements satisfactory, differ between zero, one, and two, boxes with a load cell in a mini-flow rack.

Figure 4.6: Picture from the test with the load cell in the mini-flow rack. The load cell is mounted in the front. (Authors' image)

Distance Sensor

A distance sensor of some kind can be used to measure the length of the queue of containers in a flow rack. Based on the Theoretical Framework, ultrasonic, laser, and IR sensors were identified as potential alternatives. Similar to the weight sensor, they have to be calibrated for each article. The calibrated value is later used when determining the total number of containers in a specific section of the flow rack.

From the Market Analysis, it was found that laser sensors have been used in combination with push feed systems, measuring the distance from the back of the shelf to the pusher, and thereby determine the inventory level. Similarly, it could be possible to use another type of distance sensor in a flow rack not equipped with a pusher. The sensor could then measure to the container furthest back instead of to the pusher. An illustration of this can be seen in Figure 4.7. However, it is considered that a performance test is needed to examine if an ultrasonic sensor can be used in a flow rack.

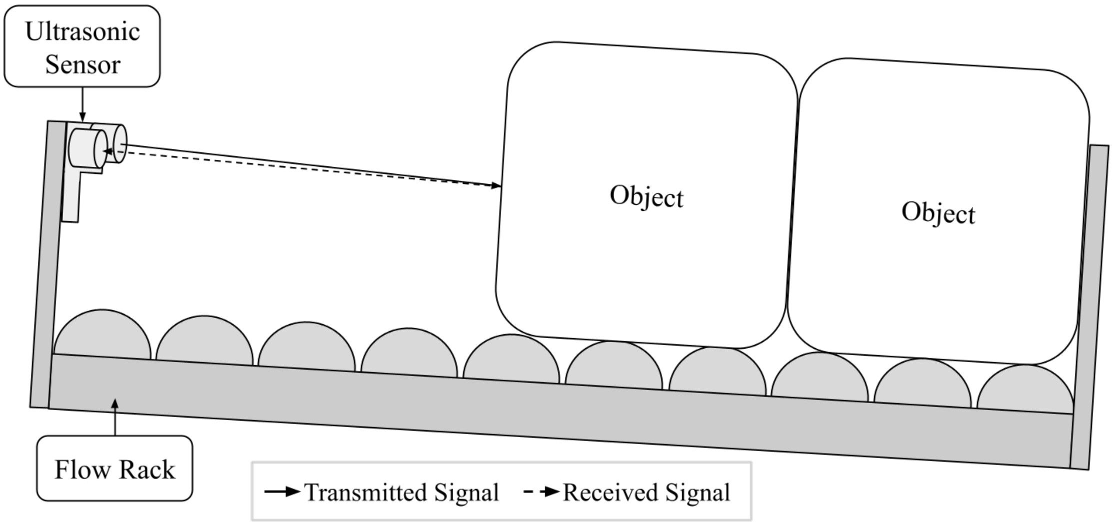

Figure 4.7: Illustration of a setup with the ultrasonic sensor in a flow rack.

The uncertainty tested is if the distance sensor can measure sufficiently narrow and thereby not be affected by objects in adjacent sections in a flow rack. The setup consisted of an ultrasonic sensor (HC-SR04) connected to a microcontroller (Wemos D1 mini). The microcontroller is connected and used in the same way as for the test of the load cell. In Appendix B, the schematic illustration of the setup can be found.

From the test, it is observed that the obtained values from the sensor are stable. It is clear that the ultrasonic sensor has a relatively small measuring width, measuring sufficiently narrow, not to be affected by objects in adjacent sections. The sensor also appears to be compact and requires a relatively small space in the mini-flow rack. Since the sensor is mounted at the back of the mini-flow rack, as seen in Figure 4.8, it will not be in the way when picking objects. However, the sensor can be in the way if the articles are refilled from the back of the flow rack. Additionally, the minimum space has to be 2 cm from the sensor to the object, otherwise the values obtained become faulty.

When no objects are placed in the mini-flow rack, the values obtained also can be faulty. The reason for this is when the signal transmitted from the sensor bounces on a rounded pipe, which can redirect the signal. However, it is with the measurements given by the ultrasonic sensor, possible to satisfactory determine how many boxes there are stored in the mini-flow rack.

Figure 4.8: Picture from the test with the ultrasonic sensor in the mini-flow rack. The sensor is mounted at the back. (Authors' image)

Contact Sensor

A contact sensor could be used to check if a container is in a specific place or not. Thereby it would be possible to determine if there is nothing or something in stock. The sensor can be mounted in the front of the flow rack, similar to the weight sensor. Based on the Theoretical Framework, this is an already well-used technology, and to use it in a flow rack is not considered to need further testing.

4.3.2 Sub-Function 2: Transmission of Data

This sub-function's central purpose is to transfer the signal from the registering node, save it, and make the data available remotely. Based on the Theoretical Framework, this can be done in several ways, depending on which technology is used for Sub-Function 1.

One way that seems promising when using sensors is to connect the sensor node to a microcontroller equipped with a WiFi module. Thereby it would be possible to send the data wirelessly to the network and thence to an IoT platform, such as Thingspeak, or a local server. Instead of WiFi, it would also be possible to use an Ethernet cable or mobile network by attaching another module to the microcontroller. For barcode and RFID technologies, the scanning device, respectively transceiver, needs to be connected to a computer where data is uploaded to a system or database. Thence the data could be sent similarly as for the sensors, as previously described.

4.3.3 Sub-Function 3: Visualization of Data

The main purpose of the last sub-function is to visualize the data generated in earlier sub-functions, which can be done in different ways. According to the Theoretical Framework, the visualization should also enable interaction with the data.

Based on the case study's current state analysis, a Virtual Twin like NavVis IndoorViewer and the digital dashboard Mevisio could be used for this purpose. Another solution is to visualize the data in a spreadsheet. In these, data could be linked from any of the chosen ways in Sub-Function 2.

4.3.4 Elimination of Concepts

All the generated concepts consist of different technologies for Sub-Function 1. Solutions for Sub-Function 2 and 3 are unspecified since the focus of the project's aim is to explore different technologies for register inventory levels. Hence, five concepts are generated and evaluated in the elimination matrix. The elimination criteria used are listed in Table 4.4. The fulfilled criteria are marked with a plus (+), and unfulfilled are marked with a minus (-). The conclusion column in the elimination matrix, presented in Table 4.5, shows that only the concepts based on the weight sensor and distance sensor fulfill all the criteria.

Table 4.4: Elimination criteria that are used in the elimination matrix.

Criteria	Description
A (Demand)	*Scope*: Avoid material shortages and digitalize data
B (Demand)	*Frequency*: Daily update of inventory levels
C (Demand)	*Precision*: Number of boxes in the inventory
D (Wish)	*Manual handling*: Avoid manual handling

As seen in Table 4.5, the barcode and RFID concepts are eliminated due to the increased manual handling. The barcode concept is eliminated since it requires a manual scanning procedure for incoming goods and emptied boxes. The manual handling would also increase for the RFID concept as it requires the manual attachment of transponders or refilling of reused bins. The contact sensor concept is eliminated since the precision is too low. The sensor cannot detect the number of boxes, which is a demand. The concepts remaining after the elimination are based on the weight sensor and distance sensor.

Table 4.5: Elimination matrix, showing which concepts to eliminate and keep.

	Criteria					
Concept	A	B	C	D	**Comment**	**Conclusion**
Barcode	+	+	+	-	The manual handling will increase, compared to the current state	Eliminate
RFID	+	+	+	-	The manual handling will increase, compared to the current state	Eliminate
Weight Sensor	+	+	+	+	Fulfills all criteria	Keep
Distance Sensor	+	+	+	+	Fulfills all criteria	Keep
Contact Sensor	+	+	-		Can only detect if there is nothing or something in the flow rack	Eliminate

4.4 Concept Integration and Visualization

The concepts that are integrated and visualized are weight sensor and distance sensor. In these concepts, a load cell respectively an ultrasonic sensor is chosen for Sub-Function 1. The cost for the components used for Sub-Function 1 is 280 SEK and 160 SEK for the load cell setup respectively, the ultrasonic setup. In both of the concepts, the same solution for Sub-Function 2 and 3 are used. For Sub-Function 2, WiFi and ThingSpeak are selected, and for Sub-Function 3, NavVis IndoorViewer.

The microcontroller is programmed as in the previous test phase but with an expansion of the code. The code, which is different for the weight sensor and the distance sensor, is presented in Appendix C respectively Appendix D. The expansion enables the output values to be sent through WiFi to ThingSpeak, which is possible since the microcontroller has an attached WiFi-module. In the evaluation test, the data generated from the sensors are retrieved from ThingSpeak. The data is displayed in a graph, seen in Figure 4.9, presenting the output value from the load cell, the ultrasonic sensor, and the true number of boxes. The output values are gathered every 15 seconds.

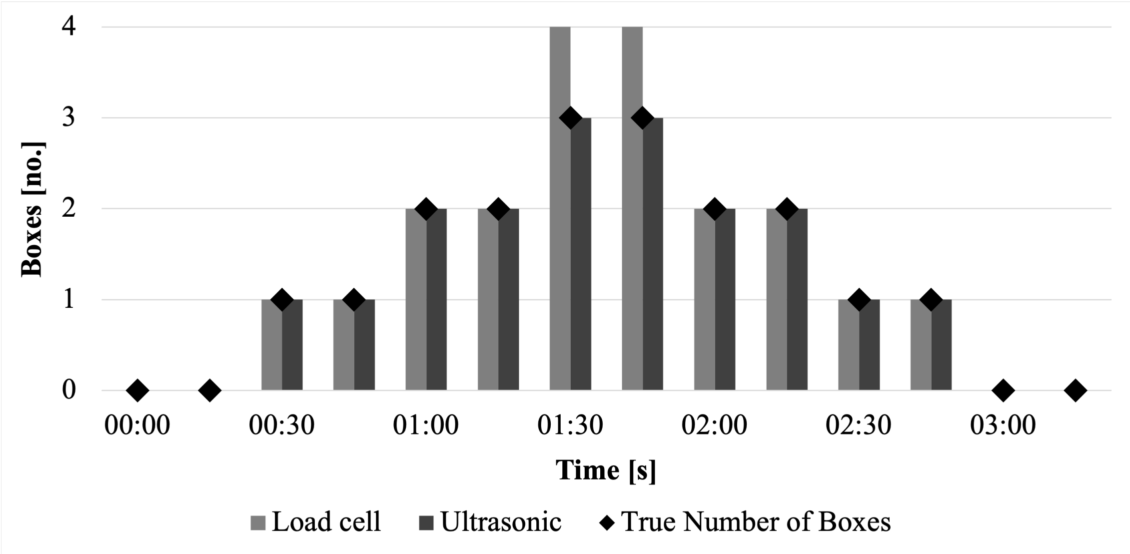

Figure 4.9: Graph showing the output values of the two evaluation tests, together with the true number of boxes.

As seen in the graph in Figure 4.9, the load cell gives false values of four boxes when the true number is only three. The ultrasonic sensor detects the correct number of boxes. The precision of the ultrasonic sensor is therefore considered more accurate than the load cell. Another additional observation is that the boxes could get stuck in the flow rack, not sliding down, which affects the registration of inventory levels in both concepts. From the evaluation test of the ultrasonic concept, it is seen that the sensor is negatively affected by the increased length of the flow rack compared to the mini-flow rack used in the test phase in Section 4.3.1. The ultrasonic sensor still measures sufficiently narrow and precise, but the installation and calibration must be done carefully to secure the correct position and direction of the sensor.

It is observed that ThingSpeak, which is used for Sub-Function 2, can save up to 100 values. After 100 values are registered, the oldest value is overwritten. Hence, depending on the frequency the microcontroller sends data to ThingSpeak, only values from a certain period is saved. Some observations directly related to the behavior of the microcontroller are also identified. The output values generated by both concepts sometimes fluctuate due to temporary disturbances such as loss of connection and hits.

In the iterative improvement process of the microcontroller's behavior, one type of filter is tested. With the filter, the microcontroller only sends data to ThingSpeak if the measured number of boxes has changed and the values have been stable for a certain amount of time. The result from the filter is that fewer values are sent to ThingSpeak and that the values visualized are less fluctuating.

The output values are visualized in ThingSpeak, using graphs and gauges, as this software can create simple visualizations besides saving data online. An example of how the graph and gauge appear in ThingSpeak is presented in Figure 4.10. To visualize the inventory level in a digital twin, NavVis IndoorViewer is used. The graphs and gauges from ThingSpeak are embedded in a POI, which can be seen in Figure 4.11. The graphs and gauges are live updated, without the need for manual refreshing.

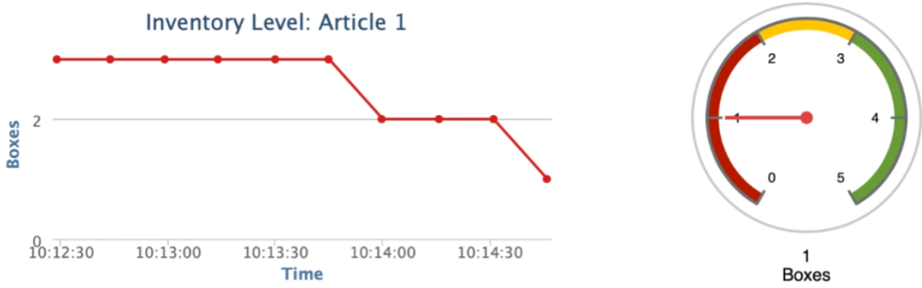

Figure 4.10: Graph and gauge provided by ThingSpeak showing the number of boxes in the flow rack.

Figure 4.11: Picture of the view in NavVis IndoorViewer. The POI for Article 1 is marked with an arrow in the center of the picture.

After the visualization of the real-time updated data from the sensors, the capabilities of the Virtual Twin increases. According to the definitions of digital twins presented in the Theoretical Framework, both levels of integration and analytics increase. With the automatic sensor data flow from the physical system to the virtual system, the Virtual Twin can be defined as a digital shadow. Considering its level of analytics, the Virtual Twin then fully fulfills the first stage, descriptive analytics, as it enables learning and understanding of what happened in the physical world.

5

Discussion

This chapter begins with a discussion of the methodology used and its results of each research question, followed by a discussion of the case study. After that, some sustainability and ethical aspects concerning both the realization of the project and its possible future outcomes are brought up. Finally, proposed future work is discussed.

5.1 RQ1

Which technologies are suitable for registering and monitoring inventory levels for real-world systems subject to inaccuracies of inventory levels?

To answer RQ1, a triangulation of methods was used. These were literature search, statistics, and market analysis, which provided qualitative and quantitative findings to the Theoretical Framework. By using multiple sources, several perspectives are covered. With other keywords and databases used for the literature search, the findings could have been different. However, to increase the reliability of the findings, only recently written articles were used in areas quickly developing, such as Industry 4.0-enabling-technologies and digital twins. The selected keywords and primary sources used for searching the market could also have affected the results. With a more extensive literature search and market analysis, additional suitable technologies could have been found. Although, it is considered that a sufficient number of technologies were identified to answer the research question.

RQ1 is answered primarily in the Comparison of Technologies, where five different technologies are identified. The criteria used for comparing the technologies were chosen with the aim to estimate the technology's overall potential to be suitable to register inventory levels and remotely monitor the data. Using other criteria could have highlighted other things. All five identified technologies were found to have potential after the initial mapping. Except for the contact sensor, all found technologies are used in similar areas of application found through the Market Analysis. Concepts that use contact sensors to register inventory levels were not identified. However, the technology is considered possible to use to check if there is or is not material at a position. Both concepts with a weight sensor and concepts with a distance sensor are validated to be suitable in the real-world system investigated. Using any of the five mentioned technologies alone does not eliminate the risk of inaccuracies of inventory levels as human errors still exist. The work procedures must be well followed to ensure articles are, for example, placed at the assigned position or scanned correctly.

5.2 RQ2

How could a concept of an inventory monitoring system be designed, using one or several technologies, to monitor inventory levels remotely?

Concepts were created to answer RQ2, with a function structure as the basis. The overall function and the sub-functions identified can be different, depending on whom identifies them. If another overall function or other sub-functions are identified, the concept design can be different. However, since the method of using a function structure traditionally is used by engineers when generating new concepts, the final result is considered to be valid. The three sub-functions that are identified for the overall function are relatively general.

For some of the generated solutions for Sub-Function 1, a test phase was performed to clarify unknown performances when implementing the technology in a flow rack. Only the weight sensor and the distance sensor were tested as it was considered that enough information was available for the other technologies. As the tests aimed to give a first hint of if the technology would be suitable to use in a flow rack, a mini-flow rack was considered enough at this stage. Thorough measurements were not conducted in the tests. However, with the test phase, a general assessment could be done, and additional knowledge not identified in the Theoretical Framework was gained. If the other technologies were tested as well, other insights could have been achieved. However, concerning their function and the extent of usage of those technologies, this was not considered essential to answer RQ2.

In the Concept Creation, all combinations of the generated solutions on each sub-function were not investigated. With the aim of the project, it was considered reasonable to focus on Sub-Function 1 and to define concepts based on how this first sub-function was to be solved. After the creation of several concepts, those that did not meet the requirements were eliminated. The requirements from the case study were used to validate the generated concepts with the case study. Depending on the outcome of the case study, the requirements could have been different, hence so would the result from the elimination matrix. However, the generated concepts are general to the specified application area.

During the Concept Creation, it was found that barcodes and RFID require manual handling and that the contact sensor has low precision. Concepts based on these technologies are therefore unsuitable for the specific system investigated. If increased manual handling or low precision is accepted where the concept is to be implemented, concepts based on these technologies could be usable. Nevertheless, this can not be ensured since further tests, similar to those done with weight sensors and distance sensors, would be needed. Weight sensors and distance sensors both passed the elimination, as they were expected to be able to fulfill the requirements also when implementing the concept in a full-scale flow rack.

5.3 RQ3

How can the concept be integrated into a real-world system and visualized in a digital twin?

In order to answer RQ3, prototypes of the concepts from the Concept Creation were built and integrated into a realistic setup. Workstation One was used for the physical setup, and the company's Virtual Twin was used for the visualization. The setup can be considered similar to the system investigated and the specified application area. If the integration instead was carried out in the real material storage area from the case study, other insights could have been gained. However, considering the similarity of Workstation One and the specified application area, insights would probably be similar to the result.

Only one of the identified solutions for Sub-Function 2, respectively Sub-Function 3, was chosen. The solutions were taken with simplicity in mind, given the project's aim and given that unnecessarily complex solutions were considered undesirable. It can be discussed whether additional solutions should have been tested. However, since the solutions chosen emerged to valuable results, supplementary solutions are not considered needed to answer RQ3.

The two integrated concepts based on weight sensors and distance sensors are, after the tests in Workstation One, proved to be able to differ between zero, one, and two boxes. When there are three boxes, only the distance sensor measures correctly. It is believed that the weight sensor is much more sensitive and only minor changes in its position affect the measurements. Stable mounting could prevent this from happening. A more neat and built-in solution could also reduce the space the weight sensor requires, but it would most likely be at a higher cost. Reduced space can lower the risk of the sensor being in the way when picking material from the flow rack. On the other hand, the distance sensor appears to be more stable but has additional problems than initially thought when the flow rack reaches a certain depth. Therefore, it becomes even more important to mount it in the correct position. The solution with a distance sensor does not take up space in the picking area but could potentially be in the way if refilling would be done from the back of the flow rack.

Besides the mounting and positioning of the sensors, the flow rack has a high impact on the measurement. Depending on the design of the box that the material is placed in, the design and resistance of the rolls, the guides that separate the sections, and the inclination of the flow rack, the material can get stuck in the flow rack. For both the weight sensor and distance sensor to measure valid values, the material must be correctly arranged in its section. If one box gets stuck, not rolling down to the front of the flow rack or the back of the box ahead, incorrect values are measured. The distance sensor will then indicate that there is more material available than it really is, and the weight sensor will measure that there is less material available than it is. It is therefore important that the design and resistance of the rollers, and the inclination of the flow rack are correct so the boxes can roll in position.

The integrated solutions can only measure the objects placed in one specific section. Neither of them can detect whether it is the correct material that is stored in the section. Nevertheless, human error is still reduced compared to using barcodes or RFID as those would require not only control of incoming goods and placement but also emptied boxes. The risk of order the wrong material is considered to be reduced with either of the solutions. As the articles in use are the only ones visualized and possible to see inventory levels on, these are also the ones that will be reordered. Using the same article numbers for ordering will ensure the same quantity and most likely same box dimensions and weight, which is crucial for the sensor to determine the correct number of stored boxes.

The integration and visualization of concepts are only done on a small scale, concerning one article and using one of each sensor at a time. Certainly, additional unknown issues are occurring when integrating several sensors to the same material storage area. These problems could be of physical characteristics, such as powering them all, but also of digital, such as visualizing the gathered data clearly. Though, there is a considerable number of existing IoT solutions that can be used for this. In some cases, hardware like a gateway will also be needed when the number of sensors increases. When using several sensors, it could also be of interest to postpone the conjunction between measured weight or distance to the number of boxes. Thereby it would be possible to program the microcontrollers the same, and later, in an IoT platform or database, determine the measured value's corresponding number of boxes.

According to the definition of a digital twin, presented in the Theoretical Framework, the Virtual Twin has a low level of data integration. With the different definitions in mind, the Virtual Twin can be defined as a digital model. However, with the integration of the generated concepts, the Virtual Twin can become a digital shadow. Depending on the further development, automatic data flow from the physical system to the virtual system and the other way around can be initialized, fulfilling the definition of a digital twin according to its level of integration. The integration of sensor data in the Virtual Twin thence proves that visualization is possible in a digital shadow. By visualizing the data in a digital twin, it would be possible to send signals back from the digital twin to the physical inventory. Such signals could, for example, be flashing lights on the flow rack when manual stocktaking seems needed or an automatic rescheduling of the production plan according to available inventory. Manual stocktaking could, for example, be initiated if the moving average and the registered inventory level do not match.

5.4 Case Study

When comparing the investigated case to what was found in the Theoretical Framework, it can be seen that Virtual Manufacturing is not a unique case facing problems with inaccuracies between physical and logical inventory. In the Market Analysis, several concepts were identified, which can prevent such inaccuracies from occurring.

Whether it would be better to deal with the reasons for material shortages by preventing the problem instead of adapting to the problem can be discussed. New work procedures can be one way to prevent the problem. However, for C-parts such as fasteners, it can be more cost-effective to have an additional system, complementing the work procedures. Though, the cost for such a supplementary system must be lower than the total cost of material shortages.

By conducting a case study, the reliability of the results increases as the findings were tested and integrated into a real case. The case was generalized by specifying the application area. With the generalization, the possibility of applying the generated concepts to other cases increased. At the same time, by specifying the application area to an inventory buffer in a flow rack, possible solutions for the system were limited.

It can be questioned how general the specified application area for the concepts is and what conclusions can be drawn when developing concepts based on this. Flow racks are not only used by the case company and are therefore not considered to be case-specific. Since flow racks are modular and can be customized, they can be used in various settings, enabling a broad area of use. For example, other parts than C-parts could be stored in a flow rack and probably use the same techniques, as for the proposed concepts, for measuring and monitoring those inventory levels. The proposed concepts could also be integrated into various flow racks, as the concepts are adaptable and scalable. With a precision level determining the number of boxes instead of the number of fasteners, more potential concepts were allowed, but these required further prerequisites.

The concepts generated require material to be stored in a standardized way. For example, the articles in one section must be stored in the same type of boxes with the same quantity in each box. Otherwise, the sensors can not determine the correct number of boxes since the calibration is specific to each article and its box dimensions. Material that is not delivered in boxes but in, for example, bags must be refilled in reusable bins. The main reason for this is since it is not preferable to store bags in a flow rack, similar to the proposed one in the Specification of Application Area, seen in Figure 4.3.

As seen in the elimination matrix, Table 4.5, both the weight sensors and distance sensors fulfill all the demands and the wish of the highest priority. For example, all the found concepts digitalize the data which, is a demand by the company. Nevertheless, all the wishes were not taken into account during the concept elimination, but they were used for support during the creation of concepts. The requirements identified from the case are company-specific, and by that, another case could have resulted in other requirements, and thereby other concepts.

The proposed concepts could be used to avoid the problem with material shortages identified in the current state analysis. It would, though, not eliminate the problem itself but rather exist as a support for the purchaser of when to purchase material.

It would also work as an aid to decide which articles should, or should not, be kept in inventory by looking at data generated and see how the inventory levels change over time. With the concept, the operators at the assembly site would not need to call the purchaser every Friday. Additionally, inventory levels can be checked remotely, without a frequent need for manual stocktaking by the operators. For the company, expenses and delayed deliveries generated by material shortages can be reduced using the generated concepts. By integrating real-time data of the inventory levels into the Virtual Twin, the first steps of transforming the digital model to a digital shadow of the production will also be taken.

The cost of the proposed concepts, exclusively material cost, will be around 160-280 SEK per section. It should therefore be of interest to invest in the proposed ones, as the concepts found on the market come at a much higher cost. However, there will be additional costs related to transmission and visualization of data, but these are difficult to estimate for the generated concepts. It is difficult mainly as the cost is strictly related to the number of sensors used and also, for example, which software is already available at the company.

5.5 Sustainability and Ethical Aspects

Throughout the project, the sustainability and ethical aspects were taken into consideration, whereas the first mentioned includes societal, ecological, and economical aspects. In the following paragraphs, these aspects will be discussed with respect to the chosen project methodology and expected outcomes after implementing the investigated concepts.

5.5.1 Societal Aspect

The assembly site of the case study is located in Linköping, but the main part of the project was conducted from Gothenburg. Therefore there was a risk of unknown changes at the site or misunderstandings due to the, mostly, remote contact with the workers in Linköping. Hence, it was crucial to arrange at least one visit to the site to get a more reliable picture of the current state and future possibilities. Due to COVID-19, the whole project was adapted to the current recommendations to prevent the spreading of the virus, through, for example, reduced traveling to Linköping and remote meetings.

One expected outcome after implementing one of the proposed concepts is reduced administrative tasks, and by so, people might lose shares of their original work. However, if operators and employees responsible for production planning and purchasing have better control over the inventory levels, stress levels can hopefully be lowered. Time could then be saved and be put on, for example, improvement work or cleaning instead. To let the purchasing department monitor the inventory levels directly and not involving any other parties, the risk of miscommunication is reduced between different departments. Additionally, by avoiding material shortage, the total productivity of the site could increase. This can, in turn, increase the company's competitiveness and thus secure continued employment for the employees.

5.5.2 Ecological Aspect

Regarding the ecological aspects of the chosen project methodology, traveling was kept to a minimum level. Instead of performing all tests at the assembly site in Linköping, tests were performed directly at Virtual Manufacturing's office in Gothenburg.

Reducing the need for last-minute purchases and thereby decrease traveling by the employees is one of the expected outcomes of the proposed concepts. As only material from standard suppliers will be purchased, the quality of the final product will be secured and possibly increased. With fewer disturbances due to material shortages, the lead time of the assembly should decrease. A decreased lead time could be positive from an ecological perspective since it indicates a higher utilization of the resources within the process. By increasing productivity, discussed earlier, the emissions of carbon dioxide per product could decrease.

One negative ecological aspect of the proposed concepts is the development and production of the technology and material required. A life cycle assessment analysis would be needed to be able to tell if that negative impact is greater than the positive impact on ecology that the concepts bring. Such detailed ecological analysis was, however, not included in this project.

5.5.3 Economical Aspect

When building prototypes and performing tests, as much material as possible was borrowed from Virtual Manufacturing, with respect to economic and ecologic perspectives. Purchased material was paid for by Virtual Manufacturing, which aims to use the material and implement some of the concepts in the future.

For the proposed concepts to be profitable, long-term savings must be higher than the cost of the components, installation, and implementation. Such expected long-term savings could come from, for example, reduced work-in-progress, fewer last-minute purchases, increased quality, reduced inventory carrying costs, and increased productivity.

5.5.4 Ethical Aspect

Finally, some ethical aspects were taken into consideration during the project as well. Interviews were conducted with, for example, some of the employees at the assembly site. During interviews, there is always a risk of misinterpreting information. Both authors were therefore present at the interviews, and the information collected was verified by the interviewees. Another aspect considered was to ensure that everyone affected by the proposed concepts was involved during the project to minimize the risk of excluding significant viewpoints.

From an ethical perspective, implementing any of the proposed concepts will hopefully result in a less stressful environment for the employees, as discussed in Section 5.5.1. Only standard suppliers will be used to deliver material in the proposed concepts since last-minute purchases from other suppliers would not be needed. Suppliers can then be selected with respect to cost but also to the company's core values. Using the same supplier can, in the long run, improve the relationship between company and supplier. Lastly, one aspect to consider is for whom the data from the proposed concepts should be available when implementing the concepts. Access to generated data must be considered to ensure secure and reliable communication.

5.6 Future Work

There are technologies, and combinations of technologies, not investigated in this project that, potentially, could be used for registering inventory levels. An image recognition system using deep learning could probably be used to detect both an article number and its quantity. Using such a system in a flow rack would, however, need to be further examined. Problems related to the design of the flow rack could, for example, arise if all objects are not visible.

Before the proposed concepts could be used large scale, it must be further investigated how the visualization of a whole material storage area could be visualized clearly. It would also be of interest to explore alternatives to, in the digital twin, highlight low levels or levels that need to be manually inspected.

In this project, only the first maturity stage of analytics of digital twins was addressed. The data generated can, with future work, be used to achieve a higher level of analytics by, for example, use BDA. With an increased level of analytics, the data can be used to forecast material requirements. In the future, a real-time connection between the data from the sensors and the ERP system in use could be advantageous to reduce inaccuracies of inventory levels. As discussed in Section 5.5.4, the security of all data must be further investigated to avoid that data is miscommunicated or that confidential data is spread.

As earlier discussed, in Section 5.4, the concept generated will not solve the root cause of the problem but rather work as a supplementary system. Further work is recommended to investigate which cases or situations it is not preferable to only solve the root cause, hence, when the supplementary system is favorable.

6
Conclusion

Barcodes, RFID, weight sensors, distance sensors, and contact sensors are investigated and found to all have the potential to be suitable for register inventory levels of boxes in flow racks. In situations where manual handling should be as low as possible, and the number of boxes must be determined, weight sensors and distance sensors can be used to register inventory levels.

Two inventory monitoring systems were designed, tested, and integrated into a real-world system during the project. They use different ways to register the levels, but besides that, the concepts are designed the same. The weight sensor, respectively the distance sensor, is connected to a microcontroller, which thence sends data to an IoT platform. Graphs created in the IoT platform were then visualized in a digital twin. The concept with distance sensor is, by the tests, proved to work satisfactional. The weight sensor, on the contrary, gives false values when there are more than two boxes in the flow rack.

From the case study, it is observed that human errors are one of the reasons for inaccuracies between physical and logical inventory. Human errors will always be present, and it can be concluded that none of the identified technologies are perfect on their own. However, a supplementary system, such as the proposed concepts, can reduce such errors and also support sustainable development. Reducing the risk of inaccurate inventory levels can, in turn, reduce the risk of, for example, material shortages, which from the case study is observed to be a consequence of the inaccuracies.

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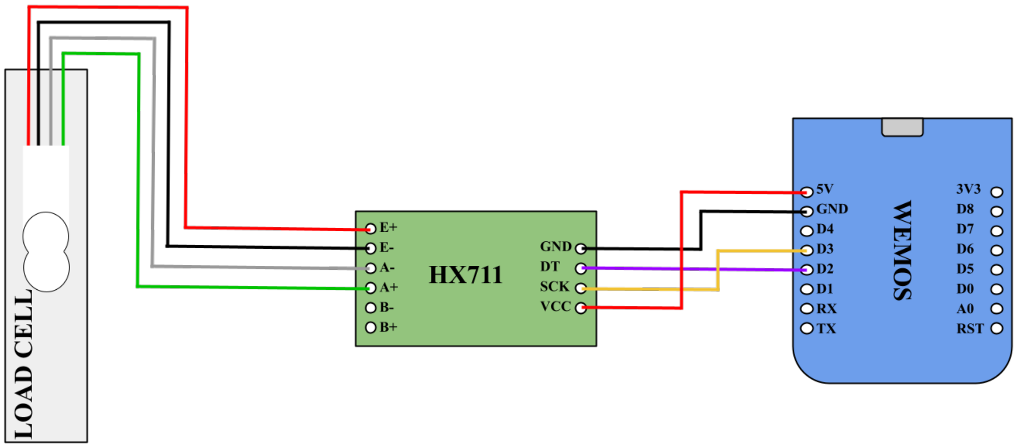
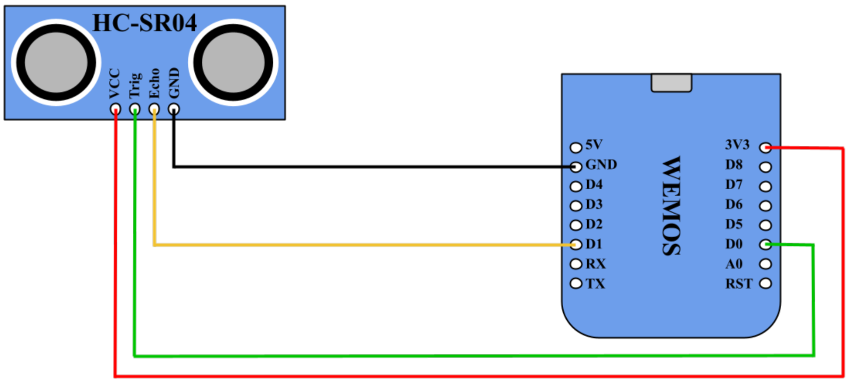
A

Load Cell Setup



B

Ultrasonic Sensor Setup



C

Load Cell Code

```
// Include Required Libraries
#include "HX711.h"
#include <ESP8266WiFi.h>
#include <WiFiClient.h>;
#include <ThingSpeak.h>;

// WiFi Settings, Name and Password
const char *ssid =  "XXX";
const char *pass =  "XXX";
WiFiClient client;

// ThingSpeak Settings, API Key and Channel Number
const char * myWriteAPIKey = "XXX";
unsigned long myChannelNumber = XXX;

// Pins used on Microcontroller
const int LOADCELL_DOUT_PIN = 4;
const int LOADCELL_SCK_PIN = 0;
HX711 scale;

// Specific Setup Parameters, Article Name and Reading Value 0 Boxes,
// the Absolute Difference of Value from 1 to 2 and 2 to 3 Boxes
int Article1 = 0;
int empty = 45174;
int boxweight1 = 25233;
int boxweight23 = 7800;

// Setup of Pins and WiFi Connection
void setup() {
  Serial.begin(57600);
  scale.begin(LOADCELL_DOUT_PIN, LOADCELL_SCK_PIN);
  ThingSpeak.begin(client);
  Serial.println("Connecting to ");
  Serial.println(ssid);
  WiFi.begin(ssid, pass);
  while (WiFi.status() != WL_CONNECTED)
    {delay(550);
    Serial.print(".");}
    Serial.println("");
    Serial.println("WiFi connected");}
// Loop to Determine Number of Boxes in Flowrack and Send the Number to ThingSpeak
void loop() {
  delay(500);
  // Save Measurement of Weight of Boxes in "reading"
  if (scale.is_ready()) {
  long reading = scale.read();
  Serial.print("HX711 reading: ");
  Serial.println(reading);}

  // Five if statements, Determining Number of Boxes after Measured Weight
  // 4, or More, Boxes in Flow Rack
  if ((reading < (empty - boxweight1 - (boxweight23 / 2) - (boxweight23 * 2)))) {
  Article1 = 4;
  Serial.print(Article1);
  Serial.print("  Article1");}
```

```
// (...)
// (Similar Code for 3 and 2 Boxes)
// (...)

// 1 Box in Flow Rack
if ((reading < (empty - (boxweight1 / 2) )) && (reading > (empty - boxweight1 - (boxweight23 / 2)))) {
Article1 = 1;
Serial.print(Article1);
Serial.print("  Article1");}

// 0 Boxes in Flow Rack
if (reading > (empty - (boxweight1 / 2))){
Article1 = 0;
Serial.print(Article1);
Serial.print("  Article1");}

else {
Serial.println("HX711 not found.");}

// Write to ThingSpeak
ThingSpeak.writeField(myChannelNumber, 1, Article1, myWriteAPIKey);}
```

D

Ultrasonic Sensor Code

```
// Include Required Libraries
#include <ESP8266WiFi.h>
#include <WiFiClient.h>;
#include <ThingSpeak.h>;

// WiFi Settings, Name and Password
const char *ssid =  "XXX";
const char *pass =  "XXX";
WiFiClient client;

// ThingSpeak Settings, API Key and Channel Number
const char * myWriteAPIKey = "XXX";
unsigned long myChannelNumber = XXX;

// Pins used on Microcontroller
int trigPin = D0;
int echoPin = D1;

// Specific Setup Parameters, Article Name, Box Length and Flowrack Length, in cm.
int Article1 = 0;
int boxlength = 9;
// (remove a half box to have the limits in the middle of the boxes, instead of at the edge of a box)
int flowrack = 64 - (boxlength / 2);

// Setup of Pins and WiFi Connection
void setup() {
  pinMode(trigPin, OUTPUT);
  pinMode(echoPin, INPUT);
  Serial.begin(57600);
  ThingSpeak.begin(client);
  Serial.println("Connecting to ");
  Serial.println(ssid);
  WiFi.begin(ssid, pass);
  while (WiFi.status() != WL_CONNECTED)
    {delay(550);
    Serial.print(".");}
    Serial.println("");
    Serial.println("WiFi connected");}
// Loop to Determine Number of Boxes in Flowrack and Send the Number to ThingSpeak
void loop(){
  delay(50);
  Serial.println("\n");

  // Save Measurement of Distance to Box in "distance"
  int duration, distance;
  digitalWrite (trigPin, HIGH);
  delayMicroseconds (10);
  digitalWrite (trigPin, LOW);
  duration = pulseIn (echoPin, HIGH);
  distance = (duration / 2) / 29.1;
  Serial.println(distance);
```

```
// Six if statements, Determining Number of Boxes after Measured Distance
// 5 Boxes in Flow Rack
if (distance < (flowrack - (boxlength * 4))) {
Article1 = 5;
Serial.print(Article1);
Serial.print("  Article1");}

// 4 Boxes in Flow Rack
if (distance >= (flowrack - (boxlength * 4)) && (distance < (flowrack - (boxlength * 3)))) {
Article1 = 4;
Serial.print(Article1);
Serial.print("  Article1");}

// (...)
// (Similar Code for 3, 2, and 1 Boxes)
// (...)

// 0 Boxes in Flow Rack
if(distance > = flowrack){
Article1 = 0;
Serial.print(Article1);
Serial.print("  Article1");}

// Write to ThingSpeak
ThingSpeak.writeField(myChannelNumber, 1, Article1, myWriteAPIKey);}
```

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