Computers in Industry 124 (2021) 103343

Contents lists available at ScienceDirect

Computers in Industry

journal homepage: www.elsevier.com/locate/compind

# Design of a reference architecture for developing smart warehouses in industry 4.0

Maarten van Geest[a], Bedir Tekinerdogan[a], Cagatay Catal[b,*]

[a] Wageningen University & Research, Information Technology Group, Wageningen, the Netherlands
[b] Bahcesehir University, Department of Computer Engineering, Istanbul, Turkey

ARTICLE INFO

*Article history:*
Received 20 March 2020
Received in revised form 19 August 2020
Accepted 20 October 2020
Available online 10 November 2020

*Keywords:*
Reference architecture
Software architecture
Smart warehouses
Case study research

ABSTRACT

Smart warehousing aims at increasing the overall service quality, productivity, and efficiency while minimizing the costs and failures. For designing the reference architecture, we apply a domain-driven architecture design approach and use the architecture design knowledge as presented in the software architecture design literature. We first provide the results of a thorough domain analysis process to smart warehouses to identify the key concerns that shape the architecture of smart warehouses. The domain model is presented using feature diagrams that show the common and variant features of smart warehouses. The domain analysis process is followed by the architecture design process, whereby we have used architecture viewpoints for modeling the reference architecture. Different businesses require different kinds of smart warehouses. Therefore, we present the generic business process model for both traditional warehouses and smart warehouses. The business modeling process is followed by the architecture design process, whereby we have used architecture viewpoints for modeling the reference architecture. Once the reference architecture is designed, a case study has been used to evaluate the proposed reference architecture. The case study has been conducted at a large warehouse in the food industry and illustrates the overall design method and presents the lessons learned.



## 1. Introduction

A warehouse is a building for storing goods for commercial purposes. Warehouses play an important role in the food supply chain and are used by different stakeholders, including manufacturers, importers, exporters, wholesalers, and transport businesses.

Warehouses are important elements of the logistics industry because their operational efficiency determines the operational efficiency of the logistics (Hong-Ying, 2009). A warehouse business consists of three parts: the goods entering management, the goods storage management, and the goods distributing management (Yongsheng and Wenling, 2004). Traditional warehouses have several drawbacks such as inefficient space management, damaged material, inefficient operations, over-handling material, and inefficient material handling equipment (e.g., unused expensive forklifts) (Kamali, 2019). Traditional warehouses are warehouses that do not operate efficiently and perform many manual tasks that cause inefficiencies (Kamali, 2019).

Similar to other industrial domains, warehouses have also evolved as a result of advancements in science and technology. Already during the first and second industrial revolutions, the function of warehouses evolved and became more specialized. The mass production of goods triggered the need for the development of larger and more specialized warehouses, which were often located close to transport hubs such as canals and railways. Later on, the use of hydraulics and electricity had a further impact on both the warehouse design and its functions. With the widely available electricity and hydraulics, warehouses became more efficient. Warehouses continued to adapt to technological innovations and changes in the supply chain. Starting from the first industrial revolution, we can now observe the start of Industry 4.0, which is characterized by smart autonomous cyber-physical systems (Tekinerdogan, 2017). With the current Industry 4.0, the notion of smart warehouses has been introduced, which denotes the increased automation of the traditional warehouse functions. This, on its turn, aims to cope with the increased complexity of the warehouse functions, provide efficient accessibility under space and quality factor constraints by minimizing the running costs of the warehouse.

* Corresponding author.
*E-mail addresses:* maarten.vangeest@wur.nl (M. van Geest), bedir.tekinerdogan@wur.nl (B. Tekinerdogan), cagatay.catal@eng.bau.edu.tr (C. Catal).

https://doi.org/10.1016/j.compind.2020.103343

Jabbar et al. (2018) stated that a smart warehouse is a warehouse that is designed to operate with maximum efficiency and integrates best practices and advanced technologies. Therefore, a smart warehouse can function at the highest level in a rapidly changing marketplace. Pickup, bookkeeping, and delivery tasks should be performed in an automated, paperless, and unmanned way in a smart warehouse (Liu et al. (2018)). Cyber-Physical Systems (CPS) that help to build virtual copies of industrial processes can transform traditional warehouses into smart warehouses. There are four components of CPS-based smart warehouses, namely robots, humans, CPS devices, and inventories. Robust localization of objects, time-efficient communication scheduling, human activity recognition, and multi-robot collaboration are considered to be the main research challenges for smart warehouse applications (Liu et al. (2018)).

In the Industry 4.0, allocating permanent locations per product (a.k.a., static slotting) is considered to be not a good practice, therefore, the new trend is the application of dynamic slotting best practice that helps to reduce the required time for delivery (Papcun et al., 2019). A new dynamic slotting technique called chaotic storage is applied by online retailers such as Amazon.com, which allows storing any product in an empty bin. The software keeps track of the product locations, and an Automated Guided Vehicle (AGV) is directed to the product using the optimized picking route (Papcun et al., 2019). Since the order-picking process typically requires 55 % of the operational activity in warehouse operations, the order picking in smart warehouses is one of the most critical issues (Latif and Shin, 2019).

To support the smart warehouse concept, smart warehouse management systems are being developed (Cogo et al., 2020). Several features such as optimal order picking, optimal product placement, and zone capacity picking, are implemented using different algorithms in smart warehouse management systems. Internet of Things (IoT) technology is also applied to design smart warehouse monitoring and control systems. The components of such an IoT-based system are sensors, network gateway, actuators, cloud and fog systems for data storage and processing, programs for data processing and visualization, and system power sources (Čolaković et al., 2020). Augmented reality is also integrated into smart warehouses because it helps to build different scenarios by placing virtual objects during experiments (Piardi et al., 2019). With the help of these technologies, smart warehouse automation provides cost-effective services, efficient retrieval and storage, and minimal delay and errors (He et al., 2018).

In recent years, several studies have proposed and discussed different types of smart warehouses, identified the key challenges, and proposed several solution directions for coping with these challenges. Nowadays, Industry 4.0 is affecting the manufacturing processes and digital transformation of organizations by applying new disruptive technologies such as edge computing, fog computing, augmented reality, deep learning, IoT, big data analytics, digital twin, and cloud computing (Catal and Tekinerdogan, 2019). With the help of these technologies and Industry 4.0, industrial systems are becoming smarter, but also several challenges are arising with respect to the quality concerns such as privacy, integrity, and security. Smart warehouses will continue to be improved using the above-mentioned technologies of Industry 4.0, and therefore, we need to build a reference architecture that can be extended with new technologies. However, very few studies exist about how smart warehouses are designed and the transitioning strategy and process to these new types of warehouses. In this context, the transitioning strategy is the approach used to move from the traditional warehouse to a smart one in an organization.

To this end, this study proposes a method for the design of a reference architecture for smart warehouses in Industry 4.0. This reference architecture is easily reconfigurable with new sensor devices, presents the required information in a transparent way, captures the component hierarchy within smart warehouses, and integrates technologies related to Industry 4.0. Therefore, the discussed reference architecture is suitable for Industry 4.0.

The main research question (RQ) of this research is defined as follows:

RQ: what is a proper reference architecture for smart warehouses?

For designing the reference architecture, we apply a domain-driven architecture design approach (Evans, 2004, 2014) and use the architecture design knowledge (Ingeno, 2018) as presented in the software architecture design literature (Martin, 2000). We first provide the results of a thorough domain analysis process to smart warehouses to identify the key concerns that shape the architecture of smart warehouses. The domain model is presented using feature diagrams that show the common and variant features of smart warehouses. The domain analysis process is followed by the architecture design process, whereby we have used architecture viewpoints for modeling the reference architecture. Different businesses require different kinds of smart warehouses. In this study, we present the generic business process model for both traditional warehouses and smart warehouses. A case study has been conducted at a large warehouse in the food industry to evaluate the proposed reference architecture. The contributions of this study are as follows:

1 A domain-driven architecture design approach is presented that can be used to design smart warehouses.
2 By using the architecture design method, a reference architecture has been designed for developing smart warehouses for the first time in literature.
3 Both the method and the reference architecture are validated using an industrial case study at a real warehouse.

The remainder of this paper is organized as follows. In Section 2, we explain the background and related work. Section 3 presents the research methodology and the resulting reference architecture. Section 4 presents the results of a case study research. In Section 5, we present the discussion section. Finally, Section 6 concludes this paper.

## 2. Background and related work

### 2.1. Background

In this research, we followed the following five stages in order: market analysis, domain analysis, business process modeling, architecture design using viewpoints, and case study. Each of these stages is explained as follows:

- *Market Analysis* (Giudici et al., 2020): To design the reference architecture of smart warehouses, first, an external market analysis is performed. During this analysis, market size, emerging technologies, policies, challenges, new trends, and policies can be investigated. We observed that several smart warehouse applications were developed for healthcare, transport, retail, and manufacturing domains. We determined the leading companies in the smart warehouse market, such as Honeywell Intelligrated, Kuka(Swisslog), SSI Schaefer, and Daifuku. Different kinds of robots, such as picking robots that can move shelves, sorting robots, handling robots, and palletizing robots, were identified. Leading companies such as Amazon and Alibaba perform 70 % of their tasks with these types of robots. There are both software and hardware vendors in the smart warehouse market. Robotics, programmable cobots, 3D printing, IoT standards, predictive maintenance, and cognitive computing are some of the recent trends in the smart warehouse domain.

- *Domain Analysis* (Köksal and Tekinerdogan, 2017): After the market analysis, a domain analysis to derive the required knowledge is performed. Domain analysis is defined as the systematic activity for deriving, storing domain knowledge to support the engineering design process. Domain analysis consists of the following two basic activities: domain scoping and domain modeling. Domain scoping identifies the scope of the domain and the necessary knowledge sources to derive the key concepts. Domain modeling aims at representing the domain knowledge in a reusable format. The scope of the domain for our purposes is the warehouse domain in general, and smart warehouse domain in particular (Köksal and Tekinerdogan, 2017; Tekinerdogan and Öztürk, 2013). Feature modeling is one of the approaches that can be used for domain modeling (Tekinerdogan and Öztürk, 2013). In this approach, the domain model is represented using feature models that can be used to present common and variable features of a product or system, and the dependencies among variable features. A feature diagram has four basic feature 'types': (1) mandatory features which are so-called must have/must include, (2) optional features which can have/or not components, (3) alternative features (XOR) in which case it must include one of the possible components, and (4) and/or features in which case at least one of the components should be included (Salma et al., 2017). This analysis is explained in Section 3.1.
- *Business Process Modelling* (Weske, 2019): After the domain analysis, a business process model is designed. We modeled the smart warehouses using the business process modeling approach. In this research, business process modeling (BPM) is used to represent the processes of smart warehouses. By creating a model for the warehouses, the process can be analyzed and improved. The improvements can make the warehouse more efficient, speed up the processes, and automate. To model the business process, the process of outgoing products is seen as the lead process, whereas the process of incoming products/restocking is perceived as a sub-process of outgoing products. Details of these activities are presented in Section 3.2.
- *Architecture Design using Viewpoints* (Demirli and Tekinerdogan, 2011): After the business process models are modeled, the reference architecture of smart warehouses using viewpoints can be designed. The architecture design can be presented using so-called architecture design viewpoints (Clements et al., 2010). Several architectural viewpoints are defined to address different stakeholder concerns. In this study, we have adopted the context diagram, decomposition view, uses view, and deployment view. The context diagram is a visual representation of all interactions of the system with external elements. A context diagram is used to illustrate the scope of the project and to clarify the various parts. Therefore, a context diagram depicts what system is to be developed and which parts and elements are required (Clements et al., 2010). The decomposition view describes modules and submodules of the system and shows how system responsibilities are divided across them. The use of a decomposition view in understanding both differences and similarities across various modules allows for parallel implementation of responsibilities as separate modules can be assigned to different teams (Clements et al., 2010). The decomposition is perceived as a fundamental architecture view as it serves as input for the upcoming views. It illustrates the structure of the software by decomposing larger modules into smaller ones. The uses view is a way of showing relations between different systems mentioned in the decomposition view. In the Uses view, an arrow is used to show the relation between the systems. A deployment view is used to analyze performance, reliability, security, and availability (Clements et al., 2010). Each view created for smart warehouses per viewpoint is explained in Section 3.3.
- *Case Study* (Uzun and Tekinerdogan, 2019): The artifacts of the reference architecture must be tested and evaluated using a case study. The case study was conducted in collaboration with the warehouse manager of a 19,500 m2 warehouse in the area near Utrecht, the Netherlands. During this case study, the reference architecture was applied, and recommendations were made. This case study is presented in Section 4.

### 2.2. Related work

Several articles discussed the development of smart warehouse applications. Some of them focus on a particular aspect of the application development (e.g., development of the data collection unit). In this section, we present the state-of-the-art of the smart warehouse solution development.

Lee et al. (2017b) designed a data collection unit (DCU) and applied it to the forklifts. Several sensors and devices, such as scale sensor, RFID reader, antenna, and mobile tag, were connected to the forklift. They concluded that this system automates the warehouse and IoT-based data transmitting system is beneficial to smart warehouses. Their focus was not the design of a reference architecture, but the development of an IoT-based system. Žunić et al. (2018) implemented a smart warehouse management system that uses optimization algorithms and artificial intelligence techniques. Stock planning, product placement, transferring to pick zones, order picking, transport, and tracking features were realized in this system. Barcodes were attached to the racks, and vehicles were tracked using the GPS module.

Lee et al. (2017a) proposed an IoT-based warehouse management system that uses computational intelligence techniques for smart logistics. They applied fuzzy logic approach to select the best order picking method and concluded that the use of IoT, Robotics, and Artificial Intelligence is the future research direction for smart warehouses. Yao et al. (2014) designed an intelligent warehouse control system that has the following components: event-handling system, wireless sensor network system, and intelligent control system. Zigbee technology was used in the wireless sensor network system. The temperature and humidity of the warehouse were monitored and controlled based on this system. Jabbar et al. (2018) proposed a web-oriented architecture for communication of objects in the warehouse, and the REST framework was used as the basis of communication between objects. Two components, namely smart warehouse services and RESTfull warehouse services, were developed. They explain how RESTfull APIs can be integrated into smart warehouse services. ZigBee sensor nodes were used in this system.

Multi-robot cooperation can improve the picking process in smart warehouses (Li et al., 2016). Multiple robots must be coordinated to handle multiple tasks, and the task assignment for each robot is a challenging problem. Li et al. (2016) designed a heuristic algorithm to solve this task assignment problem. Falkenberg et al. (2017) designed an IoT testbed called PhyNetLab to evaluate future smart logistics approaches. This testbed is considered to be a wireless sensor network testbed. A PhyNode module that consists of a display, sensors, a battery, solar cell, and radio interface is attached to each container. For the development of new energy-efficient communication protocols, this type of testbeds simplifies the development process. Bolu and Korçak (2019) presented a collision-free path planning algorithm for smart warehouses and showed that the algorithm works effectively in the case of the different number of robots and different warehouse design cases.

According to our literature analysis presented in this section, studies mostly focused on the use of IoT technology, designed some devices and testbed platforms, and focused on a particular problem in the smart warehouse domain. To the best of our knowledge, a reference architecture for developing smart warehouses has not been proposed in literature yet.

## 3. Methodology

As outlined in this section, our methodology included well-established approaches in software engineering and particularly, software architecture. Researchers of this study have been applying these approaches in the design of large-scale software-intensive systems for more than ten years.

### *3.1. Domain analysis*

In Section 3.1.1, we present the domain model of smart warehouses.

#### *3.1.1. Smart warehouses*

Fig. 1 presents a feature diagram for a traditional warehouse. In this model, various common and variable features of the warehouse system are presented. A traditional warehouse has several top-level features such as receiving, storing, track and tracing, picking, shipping, the up and downstream stakeholders, and a management system (Won and Olafsson, 2005). Finally, a planning section, even though recommended, is optional in warehousing.

When goods arrive at a warehouse, they must be tagged. The goods can be tagged on various levels, namely at either truck level, pallet level, tray level, or product level. Pallet and tray are the most common ones due to their efficiency and provide a relative distinction between the various products. Next, the goods are stored, which happens through manual labor or by conveyer belts, and optionally the compatibility of hazardous goods is inspected and stored accordingly.

In a traditional warehouse, products are tracked manually, often with handheld scanners. The planning department is responsible for order planning. It has to determine what order is processed when and with which resources. After the order is planned, the order is picked. The order-picking is done manually as well. Goods can be picked by its tray/pallet, but sometimes batches have to be customized, and various goods are manually assembled to meet the order. Finally, the order is prepared for shipment and shipped after.

The supply chain of a warehouse has both upstream and downstream stakeholders. The upstream stakeholder is the supplier. The upstream stakeholders are responsible for supplying the warehouse with its goods. The downstream stakeholder is the customer. The downstream stakeholders place an order at the warehouse, which is then shipped to them. Some warehouses have the same up and downstream stakeholder; this can be explained as various suppliers use warehouses to store excessive produced products. Communication is key when it comes to stakeholders. These stakeholders are requested when orders are ready, the stock is running, or when there is any deviation in the delivery process.

In the end, a warehouse has to be managed. A management system consisting of finance/accounting, data processing, and sales management is responsible. Sales management has to do with processing the various order and stock; it bridges the supply and demand. Finance/accounting is responsible for all financial aspects of the warehouse and guaranteeing it keeps operating from a financial point of view. Finally, data processing is responsible for organizing the data acquired through scanning and for processing other generic data. It collaborates with sales management to keep the shelves stocked and to ensure that the warehouse can handle the incoming supply deliveries.

Fig. 2 presents the feature diagram of smart warehouses. A smart warehouse has similar top-layer features with the inclusion of mandatory planning and a warehouse communication network, as opposed to the traditional warehouse. Each feature in the top layer has various optional and obligatory elements, which are discussed in detail below. Some of these elements have feature diagrams of their own and are marked with an indicator.

*3.1.1.1. Receiving.* In the smart warehouse, it is essential to identify all incoming goods. Only when goods are uniquely identified, they can be thoroughly processed by the system. Products can be tagged either using a barcode or an RFID-tag. The barcode is often used as a way of identifying products. However, it can only accommodate a small amount of data, and its scanning is perceived as time-consuming and can only be done from a small range (Wang et al., 2010). Radio-frequency identification (RFID) has increasingly become popular over the past few years and is perceived as more accurate, simpler, and efficient. Other than barcodes, RFID can be read from a large distance, can store a large amount of data, and allows for better data handling (Wang et al., 2015). Near-field communication (NFC) is based on RFID and has the benefit that various NFC-tags can communicate with each other. An optional feature of the Receiving feature is quality control that checks the quality of the incoming goods. For this top-level feature, barcode, RFID, NFS are the required technologies.

*3.1.1.2. Storing.* In a traditional warehouse, products are moved to their storage locations using forklifts. However, this is a time-consuming and labor-intense process. The use of automated guided vehicles (AGVs) would speed up the process and limit human interaction (He et al., 2018). Aside from AGVs, Augmented Reality (AR) can be used to store products as well. Especially during the transition process, this technology, where virtual elements are added to the physical world through a device, can significantly speed up the process and decrease the human error rate (Stoltz et al., 2017). In addition to these technologies, there is also one optional feature called compatibility constraints that take into account different constraints, such as hazardous materials. Hazardous is represented as an optional feature in the feature diagram.

*3.1.1.3. Tracking & tracing.* While the goods are at the warehouse, the system should know where all the goods are at all times. Internet of Things (IoT) ensures that the goods are in continuous contact with the warehouse's network. Scanners can be used as well to read the tags of the goods and communicate this with the warehouse management system. A scanner is a reliable solution for scanning barcodes. For the use of RFID-tags, a sensor is recommended.

*3.1.1.4. Planning.* For optimizing the order planning, the Advance Planning and Scheduling (APS) software or Differentiated Probabilistic Queuing (DPQ) can be used. The APS software analyzes various alternatives, highlighting several outcomes, and optimizing the planning and scheduling process. With DPQ, the orders are weighted and prioritized before they are assigned to an AGV.

*3.1.1.5. Picking.* With order-picking, AGV and AR are the two prime technologies. AGVs collect the goods and prepare them for shipment. By incorporating AR in a device, the requested goods/sections are highlighted, which optimizes the picking process. Sometimes, an order comes in, which requires customizations, and various goods have to be repacked together. This can be done with the use of robotics, e.g., by robotic arms. The implementation of robotics in customized order-picking depends on the frequency of occurrence. Otherwise, manual labor is a good alternative. An Order-Picking Operations System (OPOS) is also advised. This system splits orders into batches and prioritizes the batch-handling accordingly (Lam et al., 2014). The prioritizing of batches reduces travel distance and ensures more efficient use of human resources.

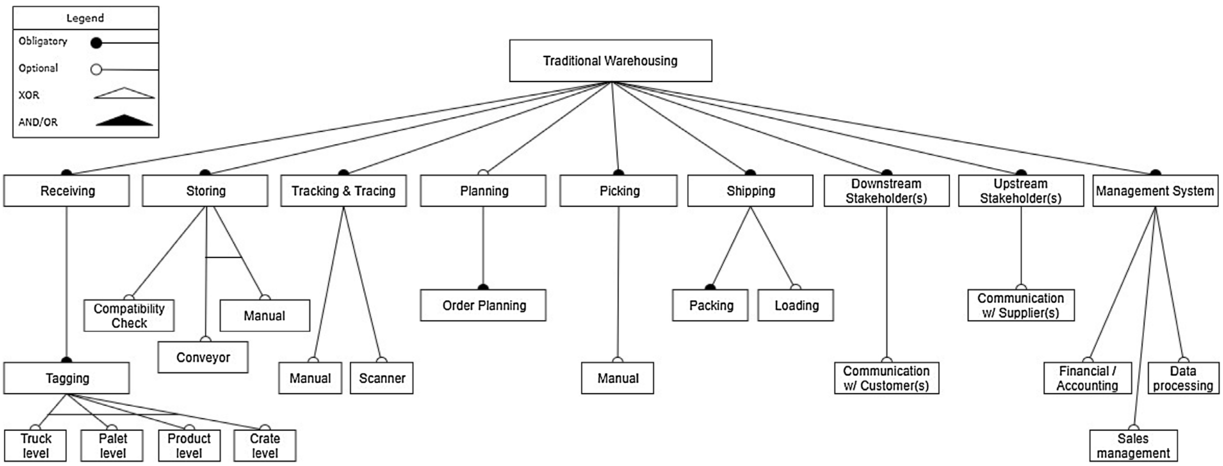


**Fig. 1.** Feature Diagram of a traditional warehouse.

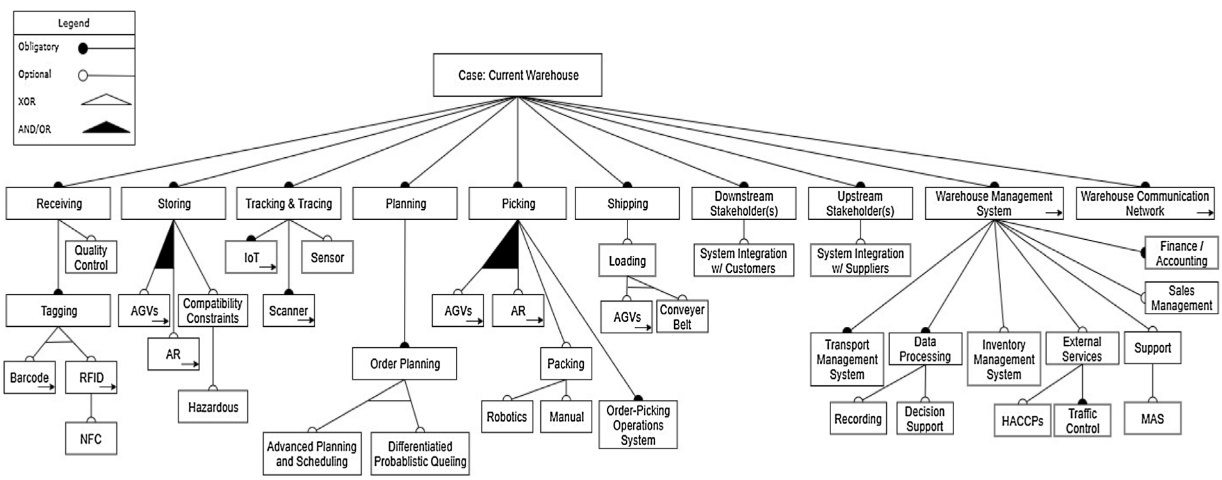


**Fig. 2.** Feature Diagram of a smart warehouse.

*3.1.1.6. Shipping.* When the order is packed and ready for delivery, the final process is the loading of the trucks. Currently, this is done with forklifts, and the use of AGVs or conveyor belts is very common. This minimizes the need for human power and is more time-efficient.

*3.1.1.7. Downstream stakeholders.* A warehouse is dependent on up and downstream partners. Downstream partners are partners that place orders at warehouses, and they are also known as clients.

*3.1.1.8. Upstream stakeholders.* Upstream partners are suppliers. To optimize tagging and systems, communication of the warehouse with its stakeholders is key. The integration of the warehouse with the supply chain will reduce costs, simplify stock management, and adds customer value.

*3.1.1.9. Warehouse management system (WMS).* The WMS brings all warehouse operations together. The WMS itself runs the warehouse and is supported by other systems. The Transport Management System (TMS) is responsible for the relocation of goods within the warehouse, both incoming and outgoing shipments. All data has to be collected, and therefore, the data processing feature has recording and decision support features. It can also be integrated with other systems such as an Inventory Management System (IMS) or be supported by a Multi-Agent System (MAS). MAS systems use the agent concept from the computer science field (Kattepur et al., 2018). Each of these agents can observe and react to the environment based on some rules and the available data. The warehouse should also be able to cope with external elements such as traffic control, integrate hazard analysis and critical control points (HACCP), or to account for overhead. Sales management and finance/accounting are the other important features of the WMS.

*3.1.1.10. Warehouse communication network.* All the components, scanners, sensors, and machinery should be able to communicate with each other. The communication within the warehouse comes down to the warehouse network (e.g., warehouse sensor network (WSN)) and the relation of various objects, systems, and actors.

### *3.1.2. The advantage of smart warehouses*

The main similarities, differences, and improvements were identified between traditional warehouses and smart warehouses by analyzing the presented feature diagrams. In this section, we first present these similarities, differences, and improvements, and then, discuss the advantages of smart warehouses.

*3.1.2.1. Similarities.*

1 They have similar features/functionalities, but the underlying technology is mostly different
2 Tagging is used in both warehouses

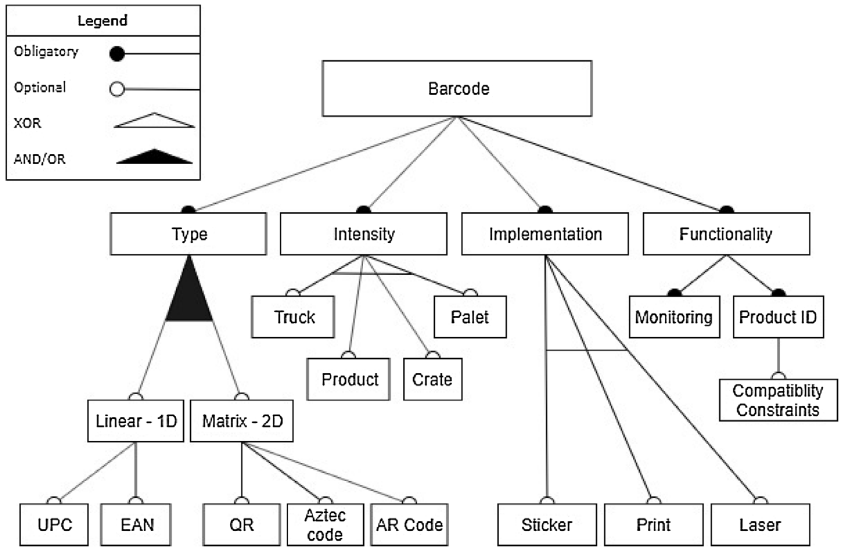


**Fig. 3.** Feature Diagram of a Barcode.

3 Data processing is performed in both warehouses, but smart warehouses apply computational intelligence techniques to discover interesting patterns
4 The scanner is used in both warehouses for tracking & tracing
5 Both warehouses have management systems

*3.1.2.2. Differences.*

1 Smart warehouses use Automated Guided Vehicles (AGV) and Augmented Reality (AR) technologies for storing components in the warehouse
2 IoT technology is applied for tracking & tracing in smart warehouses
3 Robotics, AR, and AGV technologies are applied for picking components in smart warehouses
4 AGV is used for shipping in smart warehouses
5 In smart warehouses, there is an additional communication network

*3.1.2.3. Improvements.*

1 Data processing feature is improved in smart warehouses by integrating machine learning algorithms
2 Order planning is improved with advanced techniques

*3.1.2.4. Advantages.* The main advantages of smart warehouses are presented as follows:

1 One of the most important advantages of smart warehouses is that they provide real-time information from the warehouse by using the communication network. Instant updates regarding the activities in the warehouse help to resolve the problems quicker than the traditional warehouses. This advantage is not only crucial for the organization, but also the customers who expect faster processing time.
2 Another main advantage of smart warehouses is the automation of manual tasks. Labor efficiency is improved in smart warehouses because manual tasks are replaced with more high-value tasks for the employees. This transformation minimizes the delays in sending the packages to the customers.
3 Smart warehouses also improve the operational scalability because some adjustments to the existing technological infrastructure will be less expensive than changing the human capital in the organization. Adding new IoT devices or AGVs depending on the required operational requirements can expand the operations in the organization dramatically.
4 Another advantage of smart warehouses is that they provide automated decisions. For instance, based on the historical order data and smart algorithms, the next demand per item can be predicted accurately and the positions of these items in the warehouse can be properly arranged so that the next orders are processed faster.
5 Also, smart warehouses are more adaptable to changing processes and customer demands. Since the available technologies are widely used in these warehouses, space utilization is better managed in these warehouses. The change of the processes has a minimum effect on the operation of the warehouse.
6 In smart warehouses, expensive equipment is monitored using smart devices and algorithms. This smart monitoring helps to minimize downtime risk. Also, resource waste is minimized with the help of these monitoring devices.

*3.1.3. Technologies*

The feature diagram on smart warehousing, shown in Fig. 2, has technologies marked with an indicator, being barcode, RFID, AR, AGV, IoT, scanner, WMS, and warehouse communication. The feature diagrams for these technologies are discussed in this subsection.

*3.1.3.1. Barcode.* Fig. 3 shows the feature diagram of a barcode that is the most commonly used approach in the logistics department. There are two kinds of barcodes, being linear (one-dimensional) and matrix (two dimensional) barcode. The linear barcode is the most common of which the universal product code (UPC) and the European article number (EAN) are widely accepted. The matrix barcode contains more information than the linear one, of which the quick response (QR) code is the most familiar.

It can be applied to batch levels, being from the truck to product level, and can be applied through sticker, print, or laser printing. Barcodes are used for monitoring and assigning products an identification (ID). Those IDs also register if any storing constraints are present.

*3.1.3.2. Radio-frequency identification (RFID).* Fig. 4 shows the feature diagram of RFID-tags that can store several thousand digits and is, therefore, a good tool for identifying products, including any

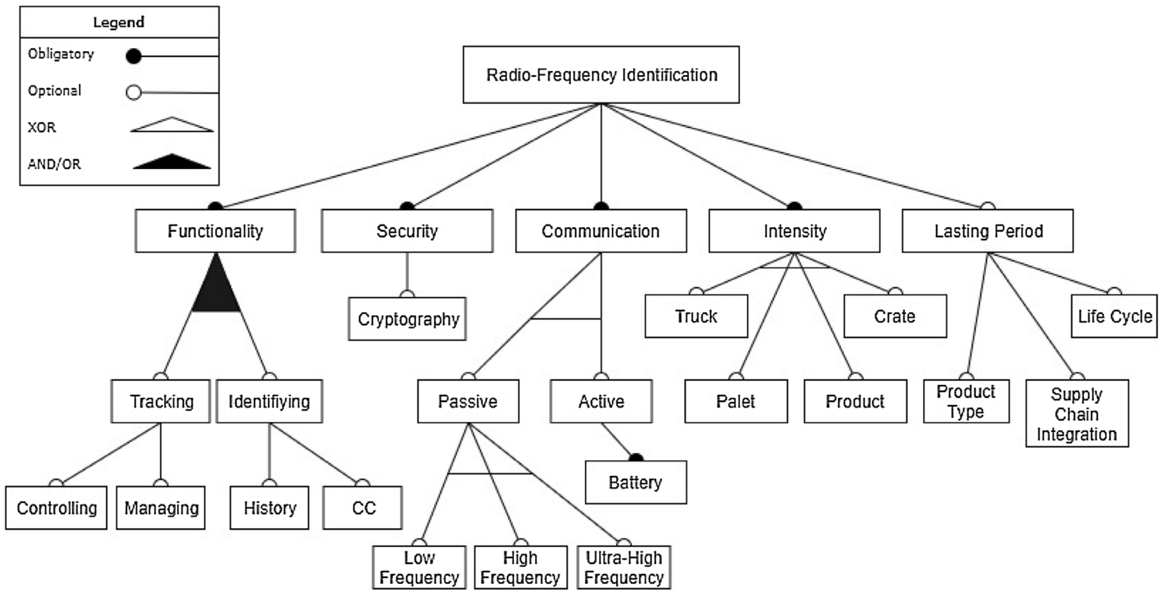


**Fig. 4.** Feature diagram of RFID-tags.

compatibility constraints (CC) and the history of the product. Facilitated by a fully integrated warehouse, this product history could add significant customer value. Aside from its identity, an RFID-tag is also used for tracking the products, and this includes controlling and managing. As with barcodes, it can be applied to all batch levels. Depending on the amount of supply chain integration, a longer life cycle of the RFID is recommended. These RFID-tags should be well encrypted to prevent others from reading it.

The RFID-tag can be either active or passive. An active tag has a battery source and continuously airs its signal. They have a bigger reading range and allow for real-time information; however, these active tags are more expensive. Passive tags do not have a power source of their own and need an RFID reader to be read. It is an economical solution that is mostly used for its tracking and smart labeling functionalities. Low and high-frequency tags have a small range, and ultra-high frequency tags allow for long-range reading.

*3.1.3.3. Augmented reality.* Fig. 5 presents the feature diagram of Augmented Reality (AR), which is an emerging technology. AR combines the physical world with virtual elements to create a new experience. The use of AR requires hardware, glasses, phones, or tablets. The wearable devices are favored as they allow the user to use his hands freely. The digital assistance provided by these devices allows for a reduction in the human error rate, improves its flexibility, and increases speed. The AR devices can read tags from either a long or short range. Finally, AR can be used for different purposes and can be controlling, guiding, or leading/directing tool.

*3.1.3.4. Automated guided vehicles (AGV).* Fig. 6 shows the feature diagram of Automated Guided Vehicles. Forklifts are frequently observed tool for transportation in a traditional warehouse. However, they are human-operated, and it is a time-consuming process. The use of AGVs would speed up this process and limit the need for human interaction. Such an AGV should be equipped with a transponder that could be either sensor or IoT-based. Supported with a transponder, an AGV is a highly efficient tool for all load transfers. It navigates through the warehouse either along with magnetic tape, an integrated grid, or its route is pre-programmed.

Safety within a warehouse is key; therefore, the AGV should be well aware of its surroundings and be suited to a traffic management system or module. Through the use of cameras and sensors, or by providing an isolated route, it can detect other vehicles, human, shelves, and any present object. An AGV can also be made autonomous, which would further restrict the need for human interaction and programming. With the use of mounted cameras on the vehicle and ceiling, it can continuously scan its surroundings. Supported by self-learning through artificial intelligence (AI) or case-based reasoning (CBR), it continuously adjusts to new situations. CBR is a technique in which previous related experience is used to support the next decision and provides the course of action (Cheng et al., 2015).

*3.1.3.5. Internet of things (IoT).* Fig. 7 shows the feature diagram of the Internet of Things (IoT). The concept of the Internet of Things (IoT) is defined as a *"dynamic global network infrastructure with self-configuring capabilities based on standard and interoperable communication protocols where physical and virtual "things" have identities, physical attributes, and virtual personalities, use intelligent interfaces and are seamlessly integrated into the information network"* (Vermesan et al., 2011). This information network can be set to provide either real-time information or at certain fixed moments.

Every object can be turned into a thing that looks like an embedded system. A thing generally has four components, namely sensors & actuators, microcontroller, a communication unit, and power supply. Therefore, IoT can be considered as the combination of physical objects, controllers, sensors, and actuators, and the Internet.

Interconnection of physical products, forklifts, pallets, and machines in a warehouse through IoT-enabled technologies such as digital twin, product intelligence, and embedded systems take into account the informational counterparts such as orders, feature descriptions, locations, and handling constraints to solve the problems (e.g., space optimization) in the warehouse. Undesirable conditions such as the high temperature and humidity in the warehouse can be managed with the help of IoT-enabled technologies and the related data collected and processed in the warehouse (Čolaković et al., 2020). The IoT-enabled warehouses can also be called Industrial IoT (IIoT) and are still at an early stage. The bandwidth and infrastructure are crucial components for the success of the IIoT if video integration is also considered in the warehouse (Jabbar et al., 2018). Also, recently market leaders in logistics introduced the first digital twins of their warehouses for cost-efficient

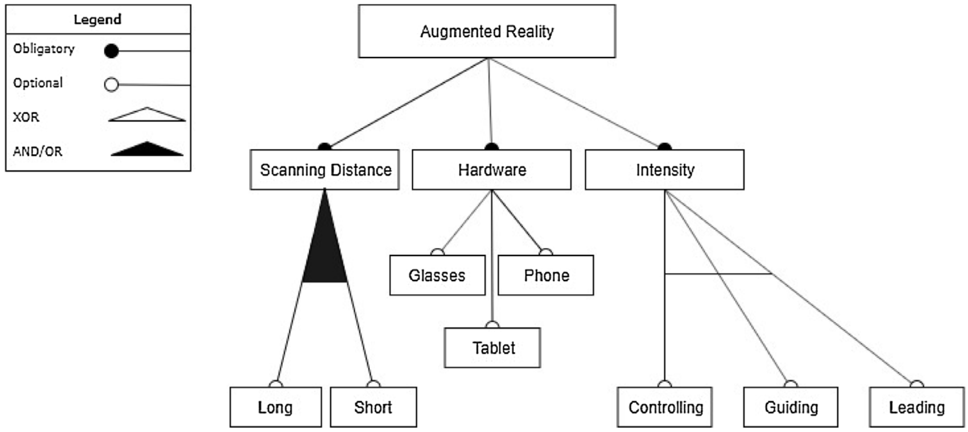


**Fig. 5.** Feature Diagram of Augmented Reality.

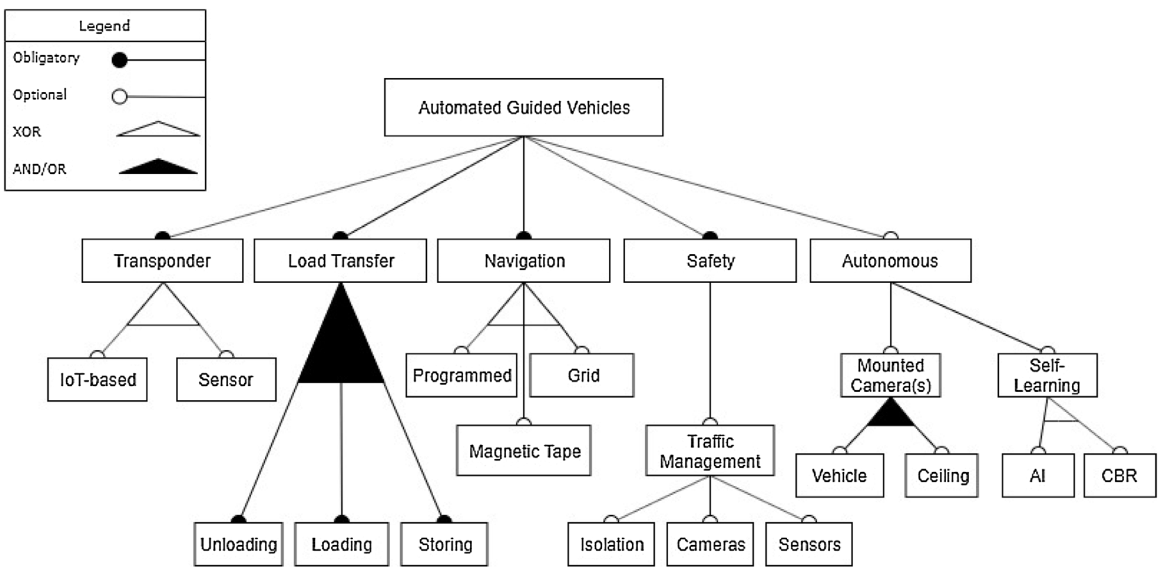


**Fig. 6.** Feature Diagram of Automated Guided Vehicles.

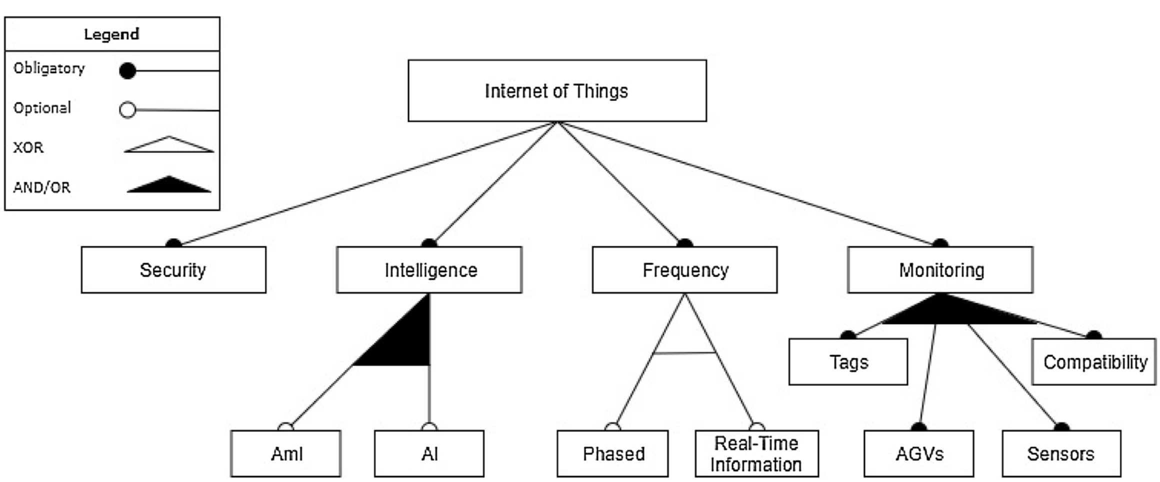


**Fig. 7.** Feature Diagram of the Internet of Things.

and optimized supply chains. Five technologies, namely IoT, Cloud Computing, Artificial Intelligence, Augmented/Virtual/Mixed Reality, and APIs & Open Standards, enable digital twins. Within the coming years, the following use cases are expected on the use of digital twins in logistics: packaging and container digital twins, digital twins of shipments, digital twins of warehouses and distribution centers, digital twins of logistics infrastructure, digital twins of global logistics networks (Gesing and Kuckelhaus, 2019).

IoT can be supported by both AI and ambient intelligence (AmI). AI enables the use of smart logistics, resulting in long-term cost reduction, better performance, and higher efficiency. The use of AI also paves the way for the use of smart robotics. AmI is a heterogeneous technology that allows for the detection of activities and interactions within the warehouse (Lee et al., 2017a). It is applied in logistics and transport to support warehouse activities and actors (Reaidy et al., 2014). It can be applied to the RFID-tags and sensors and used to communicate with AGVs.

*3.1.3.6. Scanners.* Fig. 8 presents the feature diagram of scanners. The barcodes and RIFD-tags have to be scanned and read, for which sensors and scanners are needed. A scanner should be protected with user identification to prevent fraudulent use of the scanners or to limit accessibility. Furthermore, to avoid errors and to speed up the process, most scanners are set to short-distance reading. There are variants of scanners, the remote, and the fixed scanners. The remote handheld scanners used by employees and the fixed ones are scanners at certain stages of the warehouse. The fixed scanners can be either pace on AGVs, at gateways, or at a grid for goods to pass.

*3.1.3.7. Warehouse management system (WMS).* Fig. 9 shows the feature diagram of Warehouse Management Systems. A conventional warehouse management systems (WMS) are used to monitor and handle warehouse operations and rely heavily on human input to process the data (Wang et al., 2010). In combination with other technologies such as RFID and TMS, the human input is obsolete, and the system becomes self-regulating. It is a data management tool used for the analysis and reporting of all data present. The WMS is responsible for the stock management and notifies any deviations, such as the perishability of certain products. Return management should also be considered. Returned goods should be added to the stock, and any quality check required should be performed. However, the information within the system has to be protected. First of all, no other than the appropriate employees/managers should be allowed to access. Furthermore, it should be protected from external threats, and the same goes for its servers/the cloud.

*3.1.3.8. Warehouse communication.* Fig. 10 presents the feature diagram of Warehouse Communication. The use of IoT enables an information network; however, this information should also be communicated across the different warehouse actors/operators. First of all, a communication network is required, either a wired or a wireless network. A local area network (LAN) or a wireless sensor network (WSN) are examples of wireless networks. Besides the communication network, objects should also be able to communicate with their environment, other objects, or humans. Communication with the environment comes down to up and downstream communication, whereas human interaction happens through AR.

*3.1.3.9. Other related technologies and concepts.* The above-mentioned technologies are some of the widely-used technologies in smart warehouses. In addition to these technologies, some additional advanced technologies and concepts have already been used or have the potential for future studies. The following technologies have very interesting applications in this domain:

- **Intelligent Product:** McFarlane et al. (2002) defined the intelligent product as an object communicating with its environment and having some capabilities that enable it to impact its decisions. Sallez et al. (2010) show that the augmentation concept can help to transform passive objects to active objects that can act intentionally in its environment. Cardin et al. (2016) presented the best practices for intelligent manufacturing. Several studies were performed on intelligent product concept (Kubler et al., 2013; Borangiu et al., 2014; Morariu et al., 2013; Derigent, 2012)
- **Machine Vision:** Machine Vision has been used for unstructured environments and obstacle avoidance (Espinosa et al., 2013).
- **Smart Robot Arm:** This type of arms have been mounted on AGVs (Bostelman and Shackleford, 2014).
- **Bin Picking:** Bin picking problem has been addressed with many different techniques so far (Buchholz, 2015).
- **Physical Internet:** Several researchers followed the Physical Internet vision for pallet and container identification, routing, tracking, handling, storing, and managing (Montreuil, 2011; Zhong et al., 2017).
- **Digital Twin:** Digital Twin is considered to be the digital replica of a physical object and has been applied in smart manufacturing (Qi and Tao, 2018). Lu et al. (2020) presented a review of the digital twin-driven smart manufacturing research. Leng et al. (2019) developed a digital twin to collect real-time data from a physical warehouse.
- **Machine Learning**: Machine learning techniques are used to discover knowledge from data. It has been applied for anomaly detection and other problems (Hasan et al., 2019).

### 3.2. Business process models

A smart warehouse relies on communication between and integration of systems. In the BPM of a smart warehouse, various systems are included to assist the warehouse management system in place, as shown in Fig. 11. First of all, APS software is included to guide the overall planning and scheduling processes. At the same time, an inventory management module or system is included to optimize stock management. Finance/accounting and sales management are included in the process of safeguarding all monetary flows. It is responsible for all task which requires financial interaction in one way or another, such as an incoming order or restocking. The picking of goods and orders is guided by the automated storage and retrieval system (AS/RS), this system communicates with the AGVs and any other handling mechanisms. Integrated with a transport management system (TMS), it is guiding to the AGVs and loads the trucks.

Three roles (a.k.a., swimlanes), namely Supplier/Client, Warehouse Management System (WMS), and the Warehouse are depicted in Fig. 11. The client initiates the request, and then, the supplier processes this request. Planning and management of the request are handled in the WMS. Warehouse operations are managed by the Warehouse role. Each role consists of different actions that might trigger other actions.

Aside from picking and preparing orders, the warehouse also has incoming goods, as shown in Fig. 12. As the new stock arrives, a (passive) recipients' confirmation is sent to the supplier. While the truck comes in and is unloaded, the system is updated. If needed, the quality of the products is checked, and then, the disassembled products are tagged at one of the levels, being from the truck until the product level. Once tagged, it is checked if any compatibility constraints require specific storing restrictions, and then, they are stored. The storing of goods is again guided by the automated storage and retrieval system (AS/RS). This system communicates with the AGVs and any other handling mechanisms.

### 3.3. Architecture design using viewpoints

We elaborate on the views of the reference architecture in the following subsections.

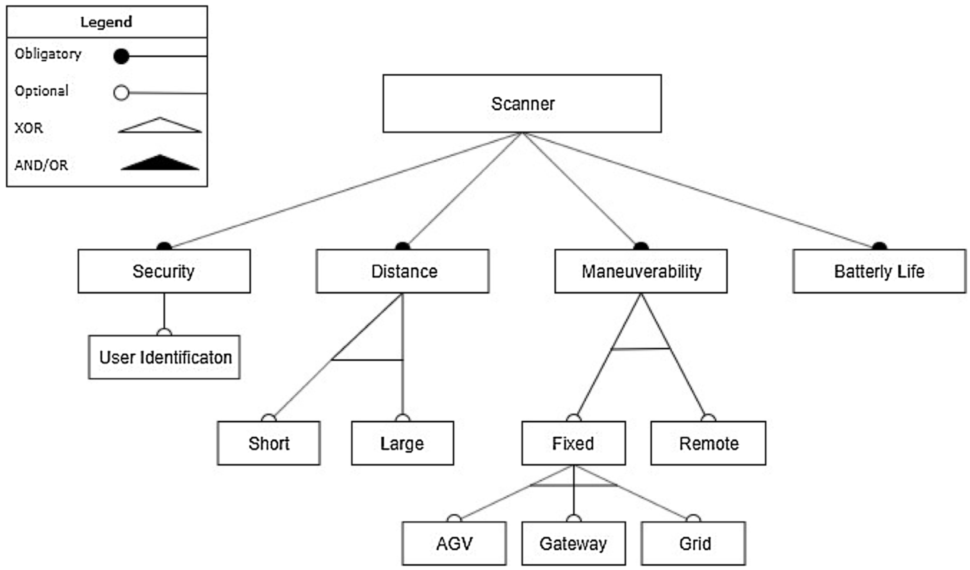


**Fig. 8.** Feature Diagram of Scanners.

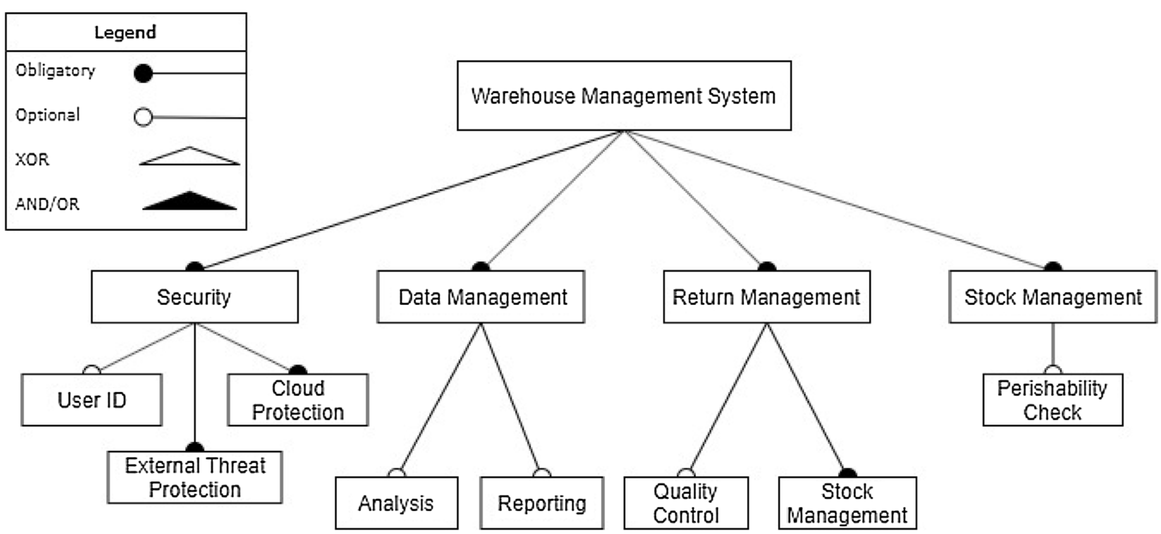


**Fig. 9.** Feature Diagram of Warehouse Management Systems.

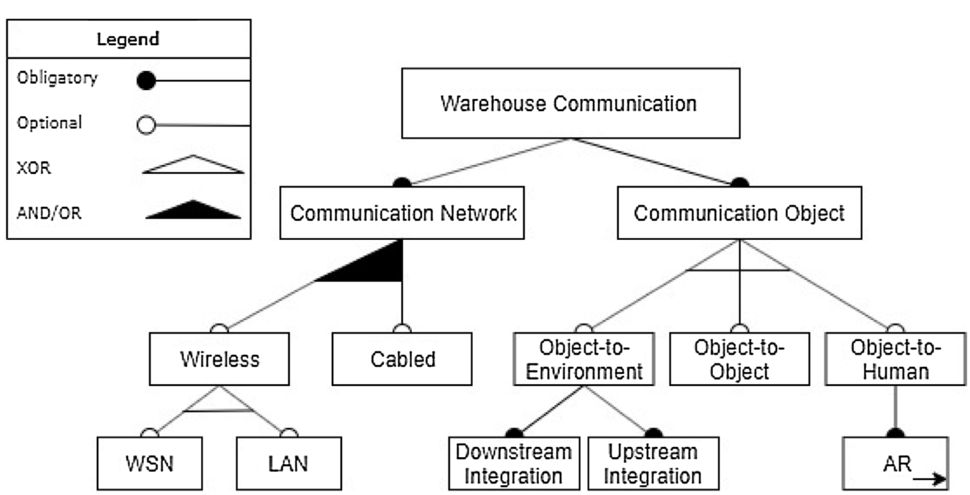


**Fig. 10.** Feature Diagram of Warehouse Communication.

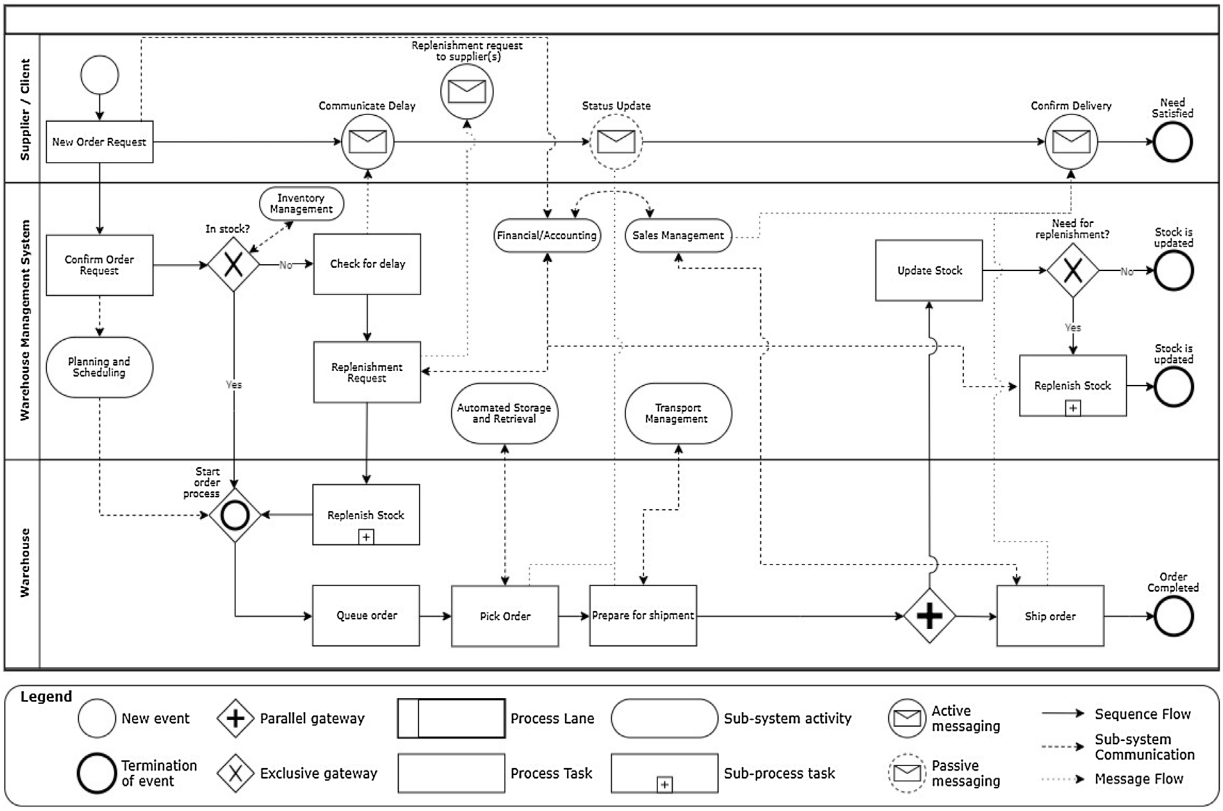


**Fig. 11.** Business Process Model of a Smart Warehouse.

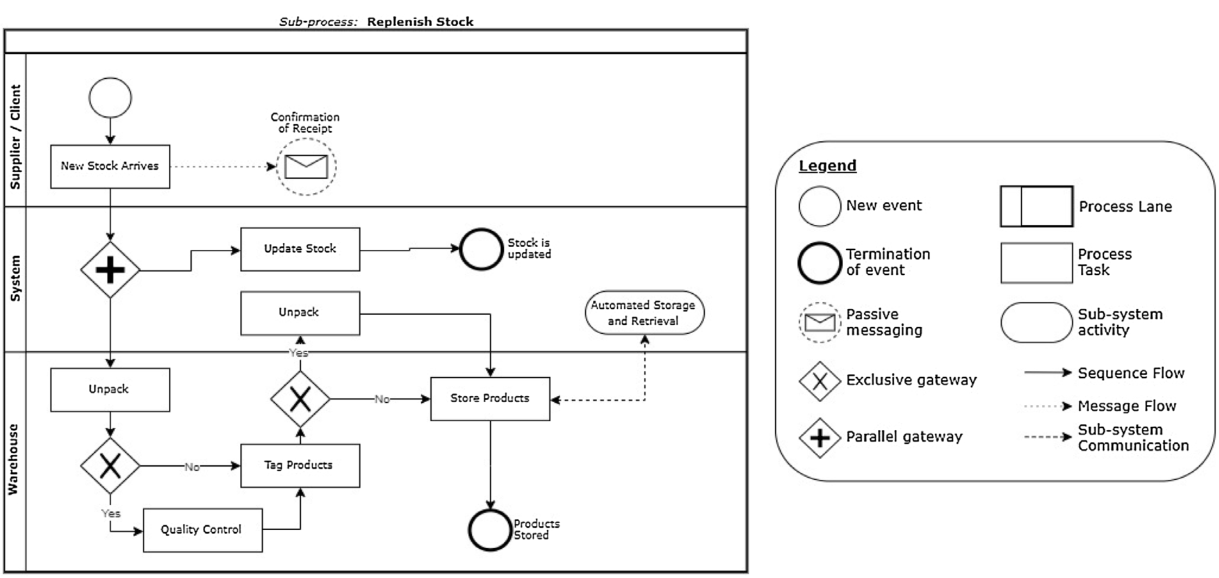


**Fig. 12.** Business Process Model of a Smart Restocking Process.

### 3.3.1. Context diagram

The context diagram for smart warehousing is presented in Fig. 13. The central system here is the warehouse management system (WMS), guiding the process through all the operations of receiving, storing, picking, and shipping. First, it interacts with various operators such as corporate supervisors, warehouse managers, and warehouse employees. These operators register actions, activities, and guide decision making in the WMS and extract reports based on the collected data. The truck drivers are an optional operator of the WMS, depending on the warehouse and its internal operations.

The WMS requires data to run properly, and to acquire this data; it relies on scanners and sensors. These scanners and sensors can be installed on AGVs or integrated into the AR hardware. The Transport Management System (TMS) directs the AGVs and employees, using AR hardware, around the warehouse, and directing them to the designated areas. This is supported by the APS system, which directs the goods to be collected. Optionally, the Order Picking Operation

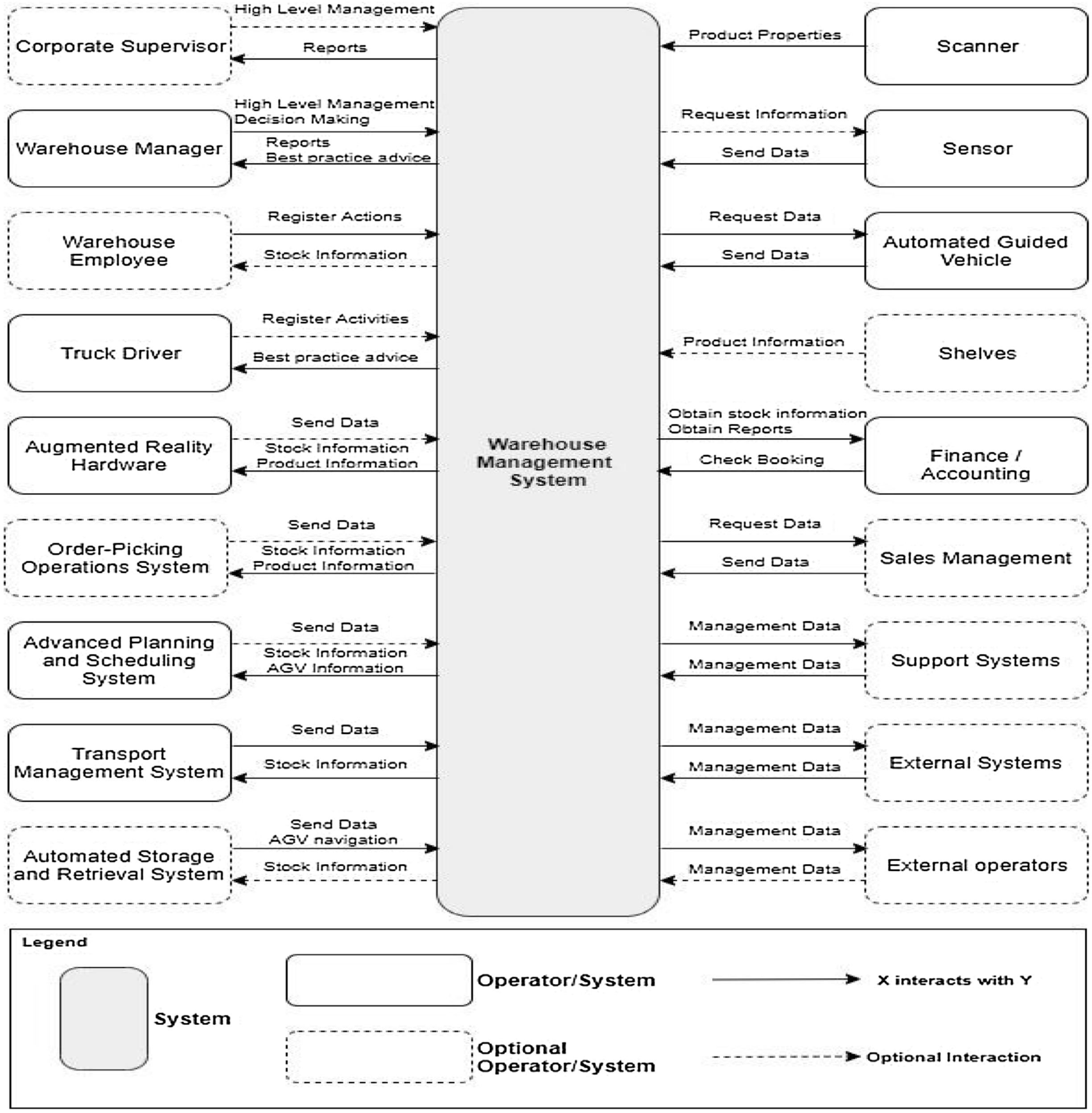


**Fig. 13.** Context Diagram.

System (OPOS) is integrated to optimize order-picking, and shelves are integrated with RFID-tags for making them self-adjusting (Zhou et al., 2017).

To optimize the warehouse processes, a MAS methodology can be applied (Kattepur et al., 2018). This requires that various agents (e.g., robotic agents) collaborate in the distributed system. Intelligent agent-based interactions can be applied among robots, and the task allocation can be performed using distributed algorithms. While the battery usage and latency can be minimized, the utilization can be maximized using decomposition techniques (Kattepur et al., 2018).

Finance/accounting, together with sales management, is responsible for all warehouse aspects that involve financial aspects. These facets are responsible for the acquisition of products and the sales, but also to pay the employees present in the warehouse. In an ideal situation, information is shared among the chain systems and actors. This is obtained through the automation of information sharing among the partners and the integration of external systems. The availability of real-time information in the warehouse speeds up the process and limits uncertainty and unexpected fluctuations.

Connectivity is the key to smart warehouse operations, and therefore, WMS communicates with other systems using communication networks. With the help of 5 G and 4 G LTE networks, the latency of the connectivity is low, and the connection is reliable. These networks make smart warehouses more agile and powerful in Industry 4.0 context. Also, especially for cloud-based warehouse systems, the hardware virtualization is mostly applied for resource sharing (a.k.a., resource pooling) (Jaekel, 2019).

### 3.3.2. Decomposition view

The decomposition view for smart warehousing is presented in Fig. 14. This view presents all the modules required for smart warehousing. Besides the top-level modules for smart warehousing, the sub-level modules for the technologies are presented as well. These technologies are barcoding, AR, AGV, Internet of Things (IoT), WMS, scanning, RFID, and communication.

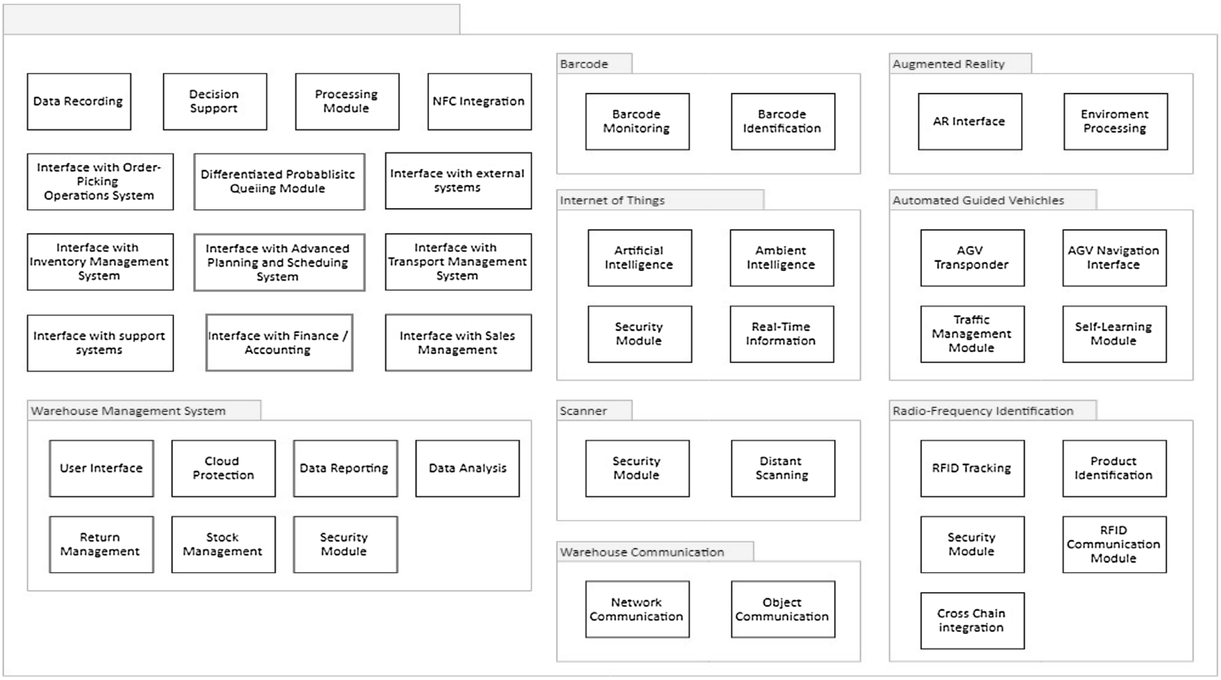


**Fig. 14.** Decomposition View.

For instance, for the IoT package, we depicted the following sub-packages in the decomposition view: Artificial Intelligence (AI), Ambient Intelligence (AmI), Security module, and Real-Time Information. This indicates that in the context of IoT, the designer of the smart warehouse should take into account the AI techniques such as machine learning and deep learning algorithms. Also, AmI that is related to the AI can bring intelligence to the warehouse environment because that is built on the concepts of AI, sensor networks, and pervasive computing. The aim of the AmI in our context is to design a smart warehouse environment that can adapt to the needs and interests of the stakeholders in the context. Real-Time Information collected from sensors and devices in the smart warehouse is used during the execution of AI and AmI algorithms. Security is one of the most important components of the IoT systems, especially Industrial IoT systems. Another sub-package shown in Fig. 14 is the Security Module that provides security controls on the IoT devices.

### 3.3.3. *Uses view*

As shown in Fig. 15, the two central modules are the WMS and the warehouse communication network. The WMS communicates with other systems, back-end modules, and the network. The network acts as a bridge between the WMS and the AR hardware or AGV. TMS, IoT, RFID, and external system also directly operate with the communication network.

### 3.3.4. *Deployment view*

In Fig. 16, the identification of the software modules to the relevant hardware is presented. The module of data processing is deployed on the Warehouse Management Server and Warehouse Manager nodes. Other nodes are devoted to cameras, sensors, scanners, and AR hardware. AGVs can have their cameras, sensors, and scanners, and shelves can have their sensors. Therefore, these features are presented with nodes of their own.

**Table 1**
Case study design.

| Case study design activity | Case: food industry warehouse |
|---|---|
| Goal | To assess the design of the architecture views<br>To assess the transition process |
| Research questions | How effective is the warehouse design approach?<br>How practical/useful is the approach? |
| Source | Warehouse Manager |
| Data collection | Semi-structured interview<br>Observation of the process and systems |
| Data analysis | Qualitative data analysis |

## 4. Case study

In this section, the architecture designs, feature diagrams, and business processes are evaluated using a case study research. In Section 4.1, we describe the adopted case study protocol. Section 4.2 presents the results of the case study research.

### 4.1. *Case study protocol*

For evaluating the developed architecture designs, feature diagrams, and business process models, a prospective case study is proposed. The case study research protocol is applied as defined by Runeson and Höst (2008). Five process steps have been identified when conducting a case study: (1) case study design, (2) preparation for data collection, (3) collecting evidence, (4) analysis of collected data, and (5) reporting. In Table 1, the design for this case study is presented. The case study is a prospective case, which encompasses a warehouse that plans to automate its processes. As mentioned before, this case study review aims to support the design and the transition process. The goal of the case study is to evaluate the developed architecture designs, feature diagrams, and business process models, and the transition process towards

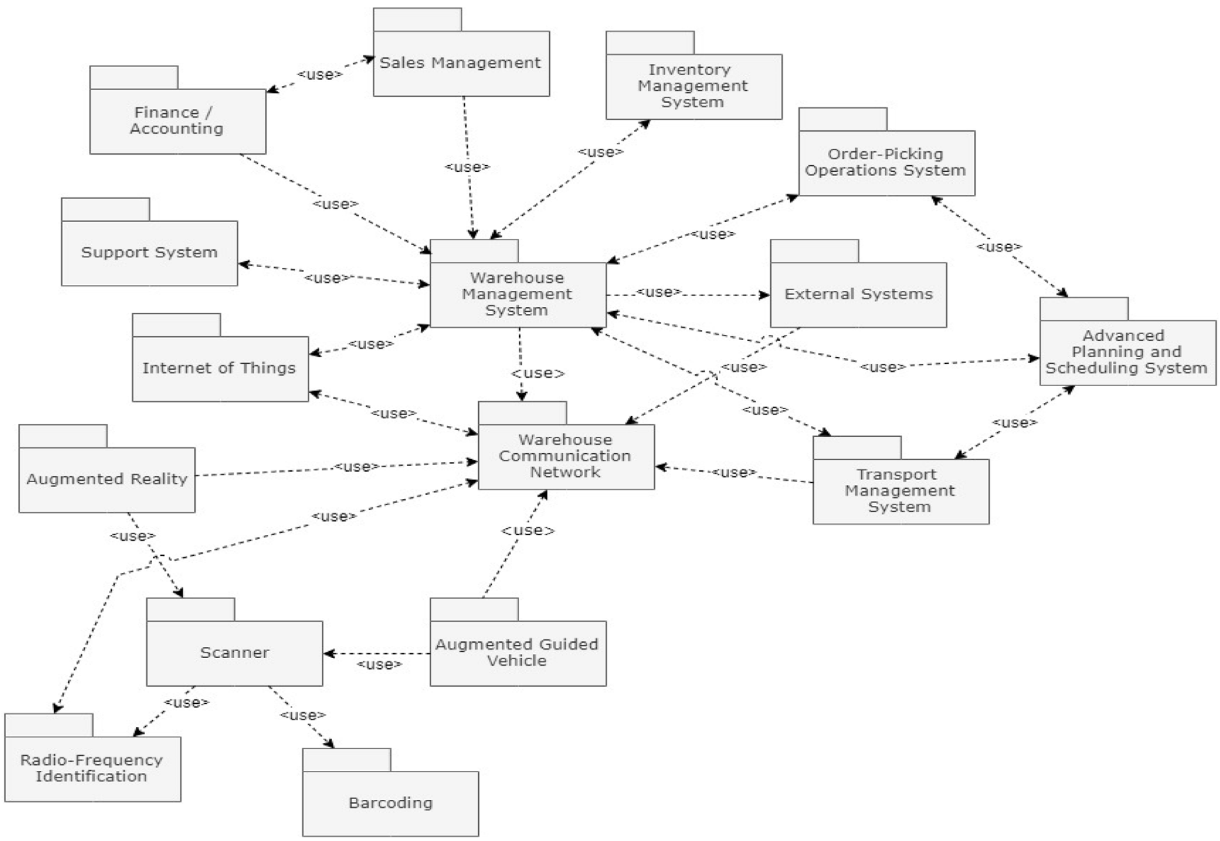


**Fig. 15.** Uses View.

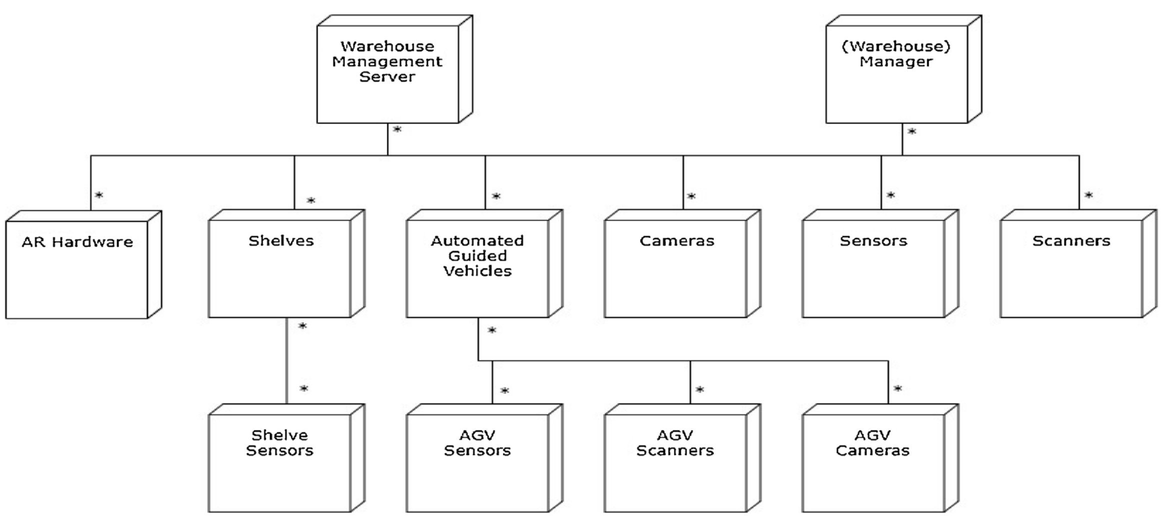


**Fig. 16.** Deployment View.

realizing a smart warehouse. Data is collected by interviewing the warehouse manager and by observing the warehouse process, both physical and system processes. The questions for the interview are presented in Table 2.

The chosen form of interview is semi-structured, and the interview is organized as follows:

1 First, an interview was planned with the warehouse manager. This interview aims to observe current practice, future plans, and background on the case company.

**Table 2**
Questionnaire for the semi-structured interview.

| Questions |
|---|
| What is the current status of automation in the warehouse? |
| As to your knowledge, are you planning to increase the amount of automation in the near future? If so, what kind of automation is this? |
| What is your opinion on the provided application architecture? |
| What is the feasibility of the application of new automation processes in this warehouse? Who has an influence on this process? |
| Do you have any suggestions for improving the method? |
| Do you have any suggestions for improving the feature models? |
| Do you have any suggestions for improving the reference architecture? |

**Table 3**
Characteristics of the case: food industry warehouse.

| Location ID | Size | # of pallets |
|---|---|---|
| Location 1 | 40,000 m2 | 60,000 |
| Location 2 | 50,000 m2 | 60,000 |
| Location 3 | 25,500 m2 | 28,000 |
| Location 4 | 19,500 m2 | 27,000 |
| Location 5 | 40,000 m2 | 60,000 |

2 Next, a tour around the premises was given, followed by a semi-structured interview. By first analyzing current practice, more follow-up questions could be asked during the interview. After the interview, a walk through the management system was given.
3 The design from Section 3 is applied to the case.
4 The design is reviewed and analyzed by the researchers.

### 4.2. Case: food industry warehouse

The supply chain industry is a highly competitive industry that invests highly in automation (Wang et al., 2010). For keeping up with market trends, companies are recommended to automate as well. One of these companies is our case, a warehouse in the food industry. This company has five (5) warehouses in the Netherlands, varying from 19,500 to 50,000 square meters, as shown in Table 3. In this case study, we focus on their smallest and most advanced one, which is located near Utrecht in the center of the Netherlands. It is 19,500 square meters in size and can store up to 27,000 pallets. Every week, about 5000 pallets are both received and shipped. Currently, the warehouse has 50 full-time employees at its disposal, guiding warehouse management and operations. Business processes such as human resources and administration transport management are operated from the largest warehouse (i.e., location 2). The case-assigned warehouse started as a public warehouse (PW) but works currently closely together with a food manufacturer. As a result, this is the only actor that rents the warehouse. However, the basic principles of a PW are still present as the company rents space, and thus does not own the stored goods.

#### 4.2.1. Domain analysis

The warehouse that we analyze closely resembles a traditional warehouse, as shown in Fig. 17. The warehouses' top features are receiving, storing, track and tracing, picking, shipping, retailer communication, and a warehouse management system. Currently, the warehouse operates with unloading the trucks and, if absent, tagging the products with a sticker on the pallet level. The barcodes are linear coded and are mainly used to provide the products with an ID. Next, the pallets are stored using forklifts. The forklift operators use remote handheld scanners to scan the barcodes and be informed on where to store everything. The scanners are locked with a user identification (user ID) and are designed for short scanning. The planned orders are picked with the use of forklifts and, if customization is requested, products are manually repacked. After the orders are readied, the truck is loaded. The warehouse has one partner company. This food manufacturer is both the supplier and the client. Communication with its partner works based on Electronic Data Interchange (EDI) standard. This method eases the electronic communication of information. Last, the warehouse management system is linked to TMS and finance/accounting.

Based on the research, interview, and observations, a feature diagram for the proposed situation is presented in Fig. 18.

The use of barcodes is recommended in the new situation. However, it is argued that the forklifts are replaced with AGVs. These AGVs have programmed routing with safety sensors to prevent collisions. Furthermore, it has transponder sensors installed to communicate its whereabouts with the WMS. Optionally, short-ranged augmented reality (AR) glasses are recommended during the transition phase. The handheld remote scanners are replaced by short-ranged fixed scanners. These scanners can be fixed on certain entry points or the AGVs.

An APS system guides the planning, and this system is supported by DPQ. After the order is planned, AGVs are used to pick the order, with programmed routing and transponder and safety sensors. Also, in the picking phase, AR glasses are recommended during the transition phase. In an automated warehouse, the manual repacking is done with robotics. After the order is readied, either AGVs or a conveyer belt is used to load the truck.

The WMS is supported by IoT, providing AI to increase the adaptability of the warehouse. Furthermore, the WMS is supported for data management; therefore, analysis can be done, and reports are made. Next, a return management system is included; this system also directs the quality control of the returned products. Besides the TMS and finance/accounting, security software is included as well to protect the warehouse from external threats. Finally, a communication network is recommended for communication.

#### 4.2.2. Business process models

Analyzing the BPM for the case warehouse concludes that the current situation is similar to the traditional warehouse, as shown in Fig. 19. The case warehouse has one fluctuation as a TMS is integrated into the system. The restocking sub-process has some small alternations as the shipment is already shipped upon arrival. In the proposed system shown in Fig. 20, an automated storage and retrieval system (AS/RS) is argued for both the storing of the new shipments and for picking the orders. Furthermore, the APS is included to support the planning of all incoming orders.

#### 4.2.3. Architecture design

In this section, the reference architecture is discussed.

*4.2.3.1. Context diagram.* Fig. 21 presents the context diagram for the case of the food industry warehouse. First of all, truck drivers are not applicable as they do not operate on the WMS. Furthermore, as smart warehousing is targeted, the warehouse employees are not included in this view. As the warehouse has one partner company, which is both the client and supplier and does not own the inventory, sales management is also excluded from this diagram. Finally, the scanners and sensors are wrapped together.

*4.2.3.2. Decomposition view.* Fig. 22 presents the decomposition view for the case of the food industry warehouse. Barcodes are recommended in this case study; therefore, RFID-tags are no longer applicable in this decomposition view. Therefore, the integration of NFCs is no longer required. The WMS has a stock management module; it was perceived that the interface with the IMS is redundant. The same accounts for the sales management module. Other modules that were excluded are barcode monitoring, ambient intelligence, the security interface module for the IoT and the scanner, the AR interface, and the self-learning module in the AGVs.

*4.2.3.3. Uses view.* As shown in Fig. 23, two central modules are the WMS and the warehouse communication network. The WMS communicates with other systems, back-end modules, and the network. The network acts as a bridge between the WMS and the AR hardware or AGV. TMS, IoT, and the external system also directly operate with the communication network. There are a few alterations compared to the reference architecture. Return management is included, whereas sales management, RFID, IMS, and OPOS are excluded in this uses view.

*4.2.3.4. Deployment view.* Fig. 24 presents the architecture deployment view. The warehouse server and manager guide the process,

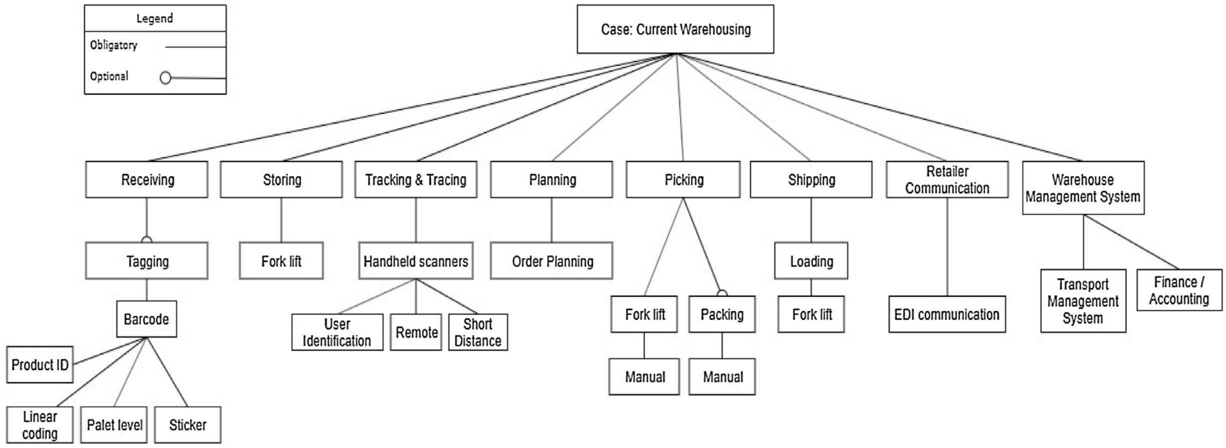


**Fig. 17.** Feature Diagram – Current Situation.

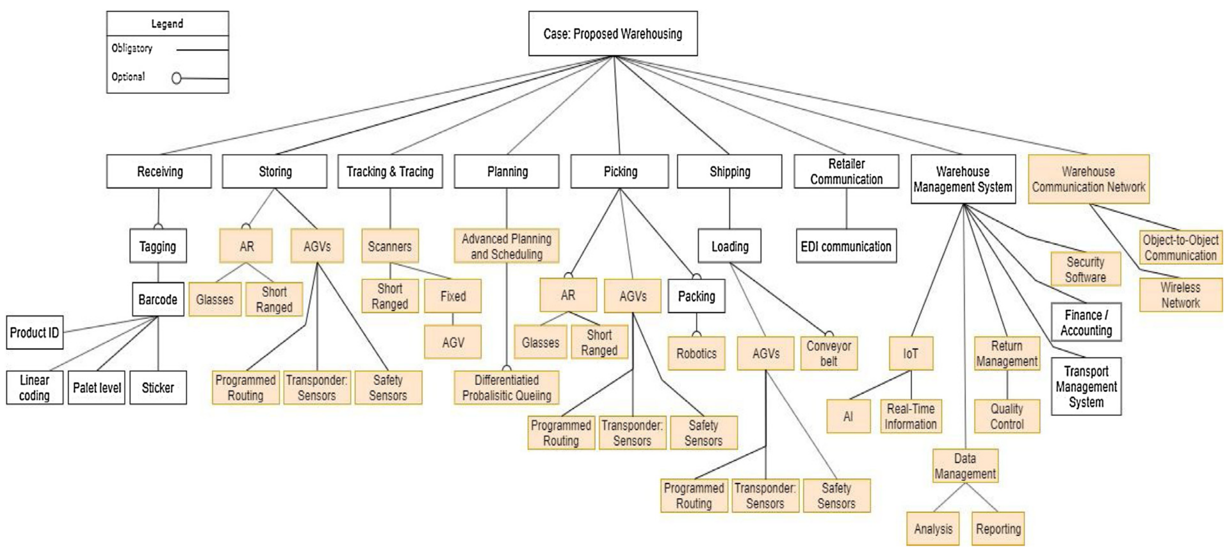


**Fig. 18.** Feature Diagram – Proposed Situation.

supported by AGVs, scanners, sensors, cameras, and AR hardware. The use of sensors on shelves remains optional.

## 5. Discussion

The reference architecture has been designed based on market analysis and domain analysis. The market analysis provides insight into the potential set of smart warehouses from the market perspective. The domain analysis results in a domain model with a common and variant set of features and modules that can be reused for developing a family of smart warehouses. Hence, the focus of the paper is a reference architecture, which is a generic architecture that can be reused to develop concrete smart warehouse architectures. Other smart warehouses can be developed based on this reference architecture using a variant set of features presented in this study. In that case, the architecture of the specialized smart warehouse is called application architecture instead of the reference architecture.

For designing a reference architecture, the first step is to select the architecture framework that defines a set of coherent viewpoints. Each viewpoint can be used to model the architecture from a particular perspective (e.g., context, decomposition, uses, deployment). The second step is to select the viewpoints from the architecture framework, which are used to model the architecture. In our study, we have chosen the Views and Beyond architecture framework (Bachmann et al., 2011) to model the reference architecture. This approach provides seventeen predefined viewpoints. We selected those viewpoints that are necessary to model the reference architecture for smart warehouses.

Also, another goal of this paper is to create a transition strategy for warehouses planning on transitioning towards smart warehousing. Therefore, the reference architecture is designed generically, so different architectural views can be derived depending on the need and plans of the party involved. However, this also means that certain niche features could have gone unnoticed and are therefore not present in this paper. Nevertheless, we believe that the architecture views create a guideline for companies planning to or working on the transition process. It is important to state that the researchers did not claim that the various designs are absolute. We believe that further research is necessary to improve the reference architecture. For example, the use of robotics besides the use of AGVs is not explored. Research in this direction would make the architecture framework more holistic.

We followed the domain-driven design (DDD) approach (Evans, 2004, 2014). The advantages of this approach are building well-defined components with very clear contracts, designing maintainable components, improving flexibility and communication, and documenting the knowledge of the domain. However,

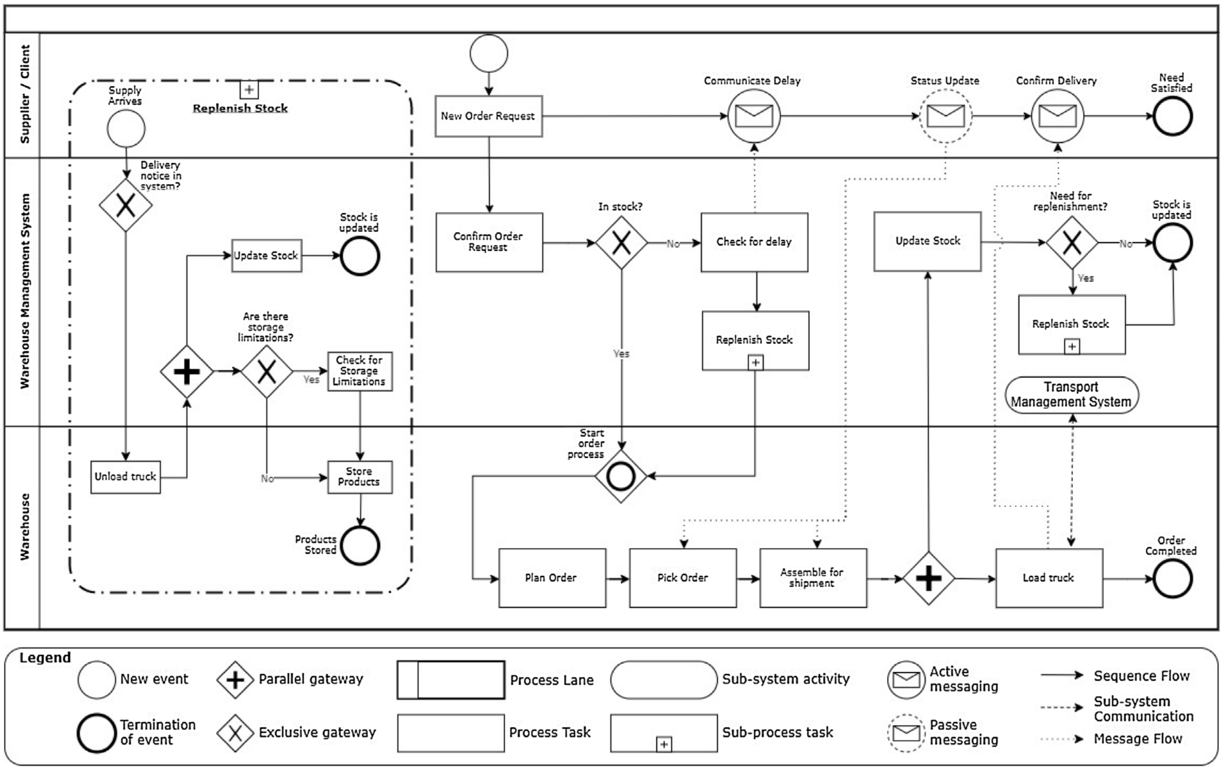


**Fig. 19.** Business Process Model – Current Situation.

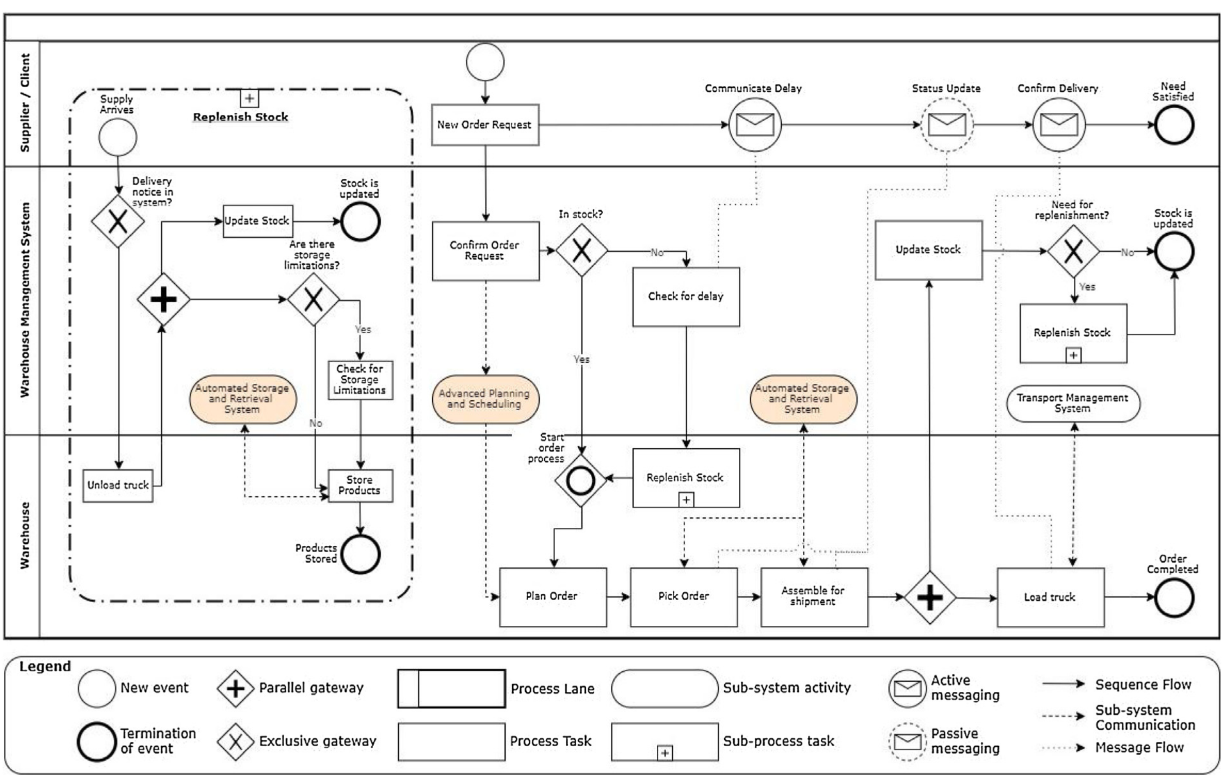


**Fig. 20.** Business Process Model – Proposed Situation.

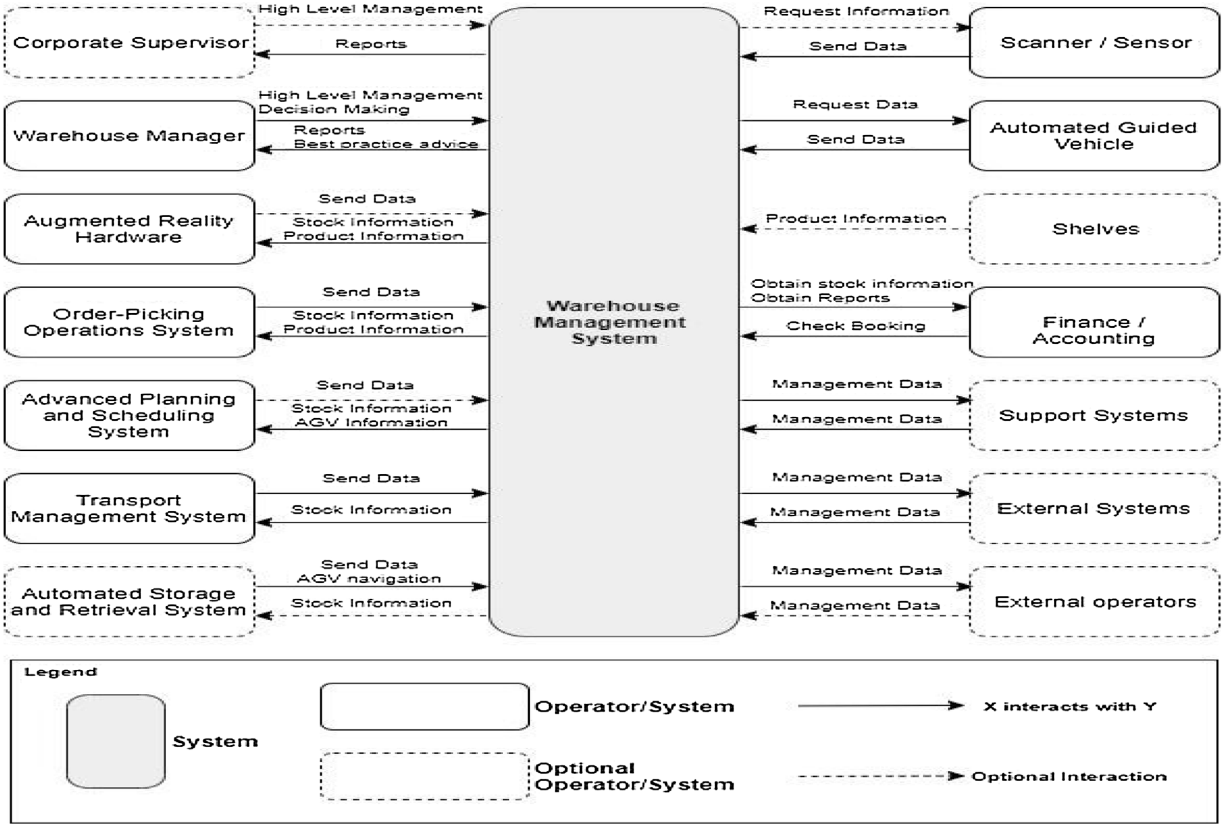


**Fig. 21.** Context Diagram – food industry warehouse case study.

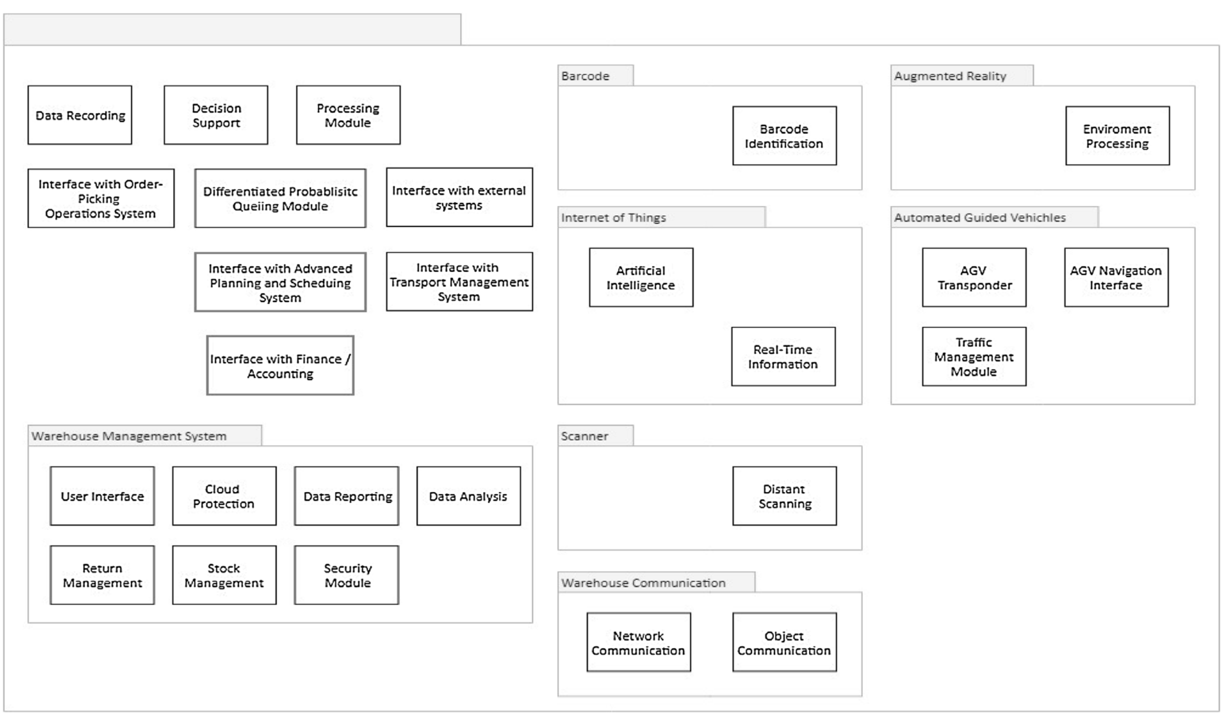


**Fig. 22.** Decomposition View – food industry warehouse case study.

there also some limitations. For instance, it requires a high cost for the development because of the required domain expertise, more work is needed, and it is mostly suited for highly technical projects performed in complex domains. For the smart warehouse domain, we preferred this approach due to its advantages.

The transition of a warehouse is an expensive and time-consuming process. For illustration, the case study warehouse is relatively small. Automating a space of 19,500 m2 is not a quick process. Even though it is explained in the paper, the various designs do not show a partial implementation of technologies during the

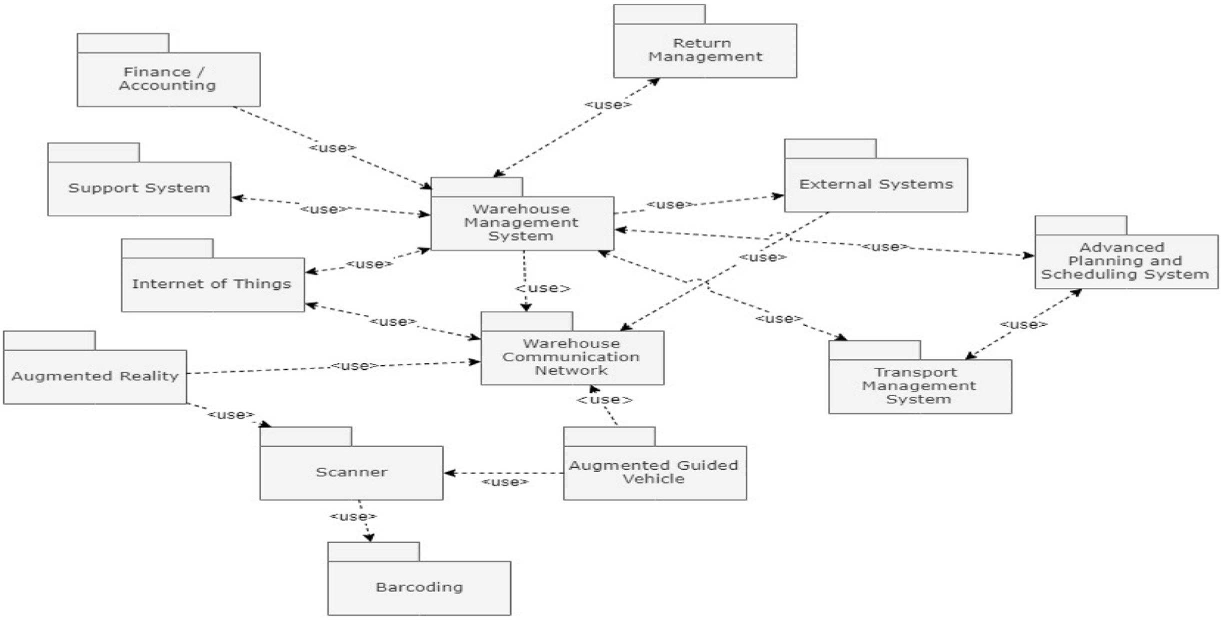


**Fig. 23.** Uses View – food industry warehouse case study.

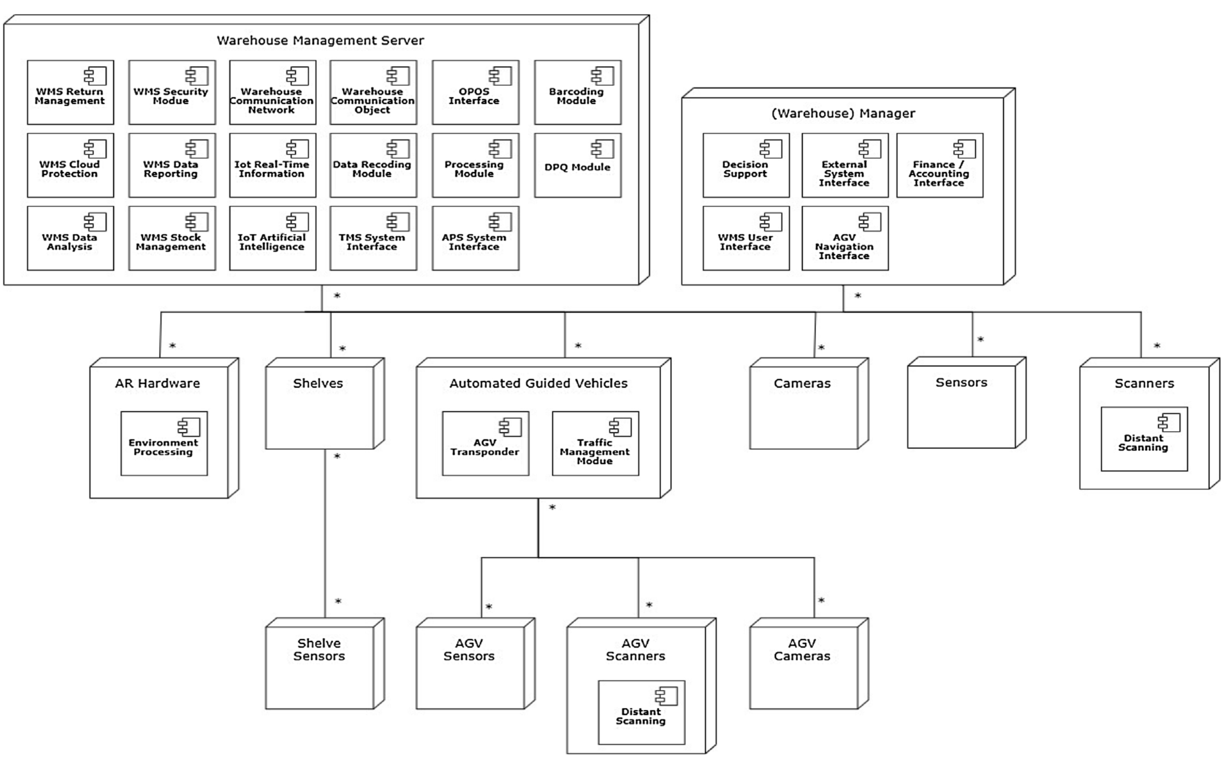


**Fig. 24.** Deployment View – food industry warehouse case study.

transition. We believe, however, that users of this paper can pick various elements from the proposed situation and apply; this will not abstain from the transition process.

The reliability of data acquired from the case study should be discussed. The data of one warehouse is used. This warehouse is thus not necessarily representable for the whole market. Even though efforts of the researchers to explain the general theory of such a view over the particular results, it cannot be excluded that this has influenced the in-depth discussion on these views. To conclude, the applied case is a prospective case study. A prospective case study aims at systems that are planned to be developed. As the proposed automation process has not started yet, no observations of the implementations could be made. Therefore, it is crucial that for the next step, a lot of data is collected and analyzed, so this model can be improved and become more accurate. As concluded in the case study, the transition of a warehouse is an expensive and time-consuming process.

The features for smart warehousing was solely obtained from peer-reviewed papers. The inclusion of other sources could result in yet unidentified features, challenges, and strategies. Such other sources are experts, software engineers, and automated warehouse platforms. Nevertheless, in such an evolving industry, new features will always emerge. Besides, this paper is aimed at introducing a transition towards smart warehousing, not as a conclusive solution of a smart warehouse. Furthermore, the systems have to be supported by various forms of hardware, as this was out of the scope of this research, further research on these aspects is required as well. For limiting the threat of misinterpretation by the researchers, questions for a semi-structured interview were formulated and discussed amongst the researchers of this paper.

## 6. Conclusion

In this study, both the design method and the resulting reference architecture for developing smart warehouses have been described and validated in a case study. To the best of our knowledge, this is the first study that explicitly focuses on the architecture design method for warehouses. For supporting the architecture design, first, a thorough domain analysis has been applied, which resulted in a domain model for representing the family of various warehouses. The domain model has been presented as a feature diagram that covers a comprehensive set of common and variant features of warehouses. With the domain model, we can characterize a broad range of warehouses and support the architecture design of smart warehouses. In parallel with the domain model, we have also provided the business process model that can be instantiated for various smart warehouses. For designing the reference architecture, we have adopted architecture viewpoints as defined in the software architecture design community. The reference architecture can be used to describe existing warehouses or prescribe and support the architecture design of new smart warehouses. We have illustrated and validated the method and the proposed reference architecture using a case study research for a large warehouse. Both the method and the reference architecture appeared to be effective and practical for designing smart warehouses based on the needs of the company. We believe that this study helps to put the focus on the architecture design of smart warehouses and pave the research for architecting smart warehouses. In our future work, we will elaborate on this study and apply the method for various other warehouses.

## CRediT authorship contribution statement

**Maarten van Geest:** Conceptualization, Data curation, Writing - review & editing. **Bedir Tekinerdogan:** Methodology, Validation, Writing - review & editing. **Cagatay Catal:** Methodology, Validation, Writing - review & editing.

## Declaration of Competing Interest

The authors report no declarations of interest.

## References


Bachmann, F., Bass, L., Garlan, D., Ivers, J., Little, R., Merson, P., Stafford, J., 2011]. Documenting Software Architectures: Views and Beyond. Addison-Wesley Professional.

Bolu, A., Korçak, Ö., 2019]. Path planning for multiple mobile robots in smart warehouse. In: 2019 7th International Conference on Control, Mechatronics and Automation (ICCMA), IEEE November, pp. 144–150.

Borangiu, T., Raileanu, S., Trentesaux, D., Berger, T., Iacob, I., 2014]. Distributed manufacturing control with extended CNP interaction of intelligent products. J. Intell. Manuf. 25 (5), 1065–1075.

Bostelman, R.V., Shackleford, W.P., 2014]. New AGV Capabilities Are Safety Driven (No. Material Handling & Logistics Magazine).

Buchholz, D., 2015. Bin-Picking: New Approaches for a Classical Problem, Vol. 44. Springer.

Cardin, O., Ounnar, F., Thomas, A., Trentesaux, D., 2016]. Future industrial systems: best practices of the intelligent manufacturing and services systems (IMS2) French Research Group. IEEE Trans. Industr. Inform. 13 (2), 704–713.

Catal, C., Tekinerdogan, B., 2019]. Aligning education for the life sciences domain to support digitalization and industry 4.0. Procedia Comput. Sci. 158, 99–106.

Cheng, S.W.Y., Choy, K.L., Lam, H.Y., 2015]. A workflow decision support system for achieving customer satisfaction in warehouses serving machinery industry. IFAC-PapersOnLine 48 (3), 1714–1719, http://dx.doi.org/10.1016/j.ifacol.2015.06.333.

Clements, P., Bachmann, F., Bass, L., Garlan, D., Ivers, J., Little, R., Stafford, J., 2010]. Documenting Software Architectures: Views and Beyond, 2nd edition) (2nd ed.). Pearson Education, Inc.

Cogo, E., Žunić, E., Beširević, A., Delalić, S., Hodžić, K., 2020. Position based visualization of real world warehouse data in a smart warehouse management system. In: 2020 19th International Symposium INFOTEH-JAHORINA (INFOTEH), ). IEEE March, pp. 1–6.

Čolaković, A., Čaušević, S., Kosovac, A., Muharemović, E., 2020]. A review of enabling technologies and solutions for IoT based smart warehouse monitoring system. In: International Conference New Technologies, Development and Applications, Springer, Cham June, pp. 630–637.

Demirli, E., Tekinerdogan, B., 2011]. Software language engineering of architectural viewpoints. In: Crnkovic, I., Gruhn, V., Book, M. (Eds.), Software Architecture. ECSA 2011. LNCS Vol 6903. Springer, Berlin, Heidelberg.

Derigent, W., June 2012]. Aggregation of Product Information for Composite Intelligent Products.

Espinosa, F., Jiménez, M.R., Cárdenas, L.R., Aponte, J.C., 2013]. Dynamic obstacle avoidance of a mobile robot through the use of machine vision algorithms. In: In Symposium of Signals, Images and Artificial Vision-2013: STSIVA-2013, IEEE. September, pp. 1–5.

Evans, E., 2004]. Domain-Driven Design: Tackling Complexity in the Heart of Software. Addison-Wesley Professional.

Evans, E., 2014]. Domain-Driven Design Reference: Definitions and Pattern Summaries. Dog Ear Publishing.

Falkenberg, R., Masoudinejad, M., Buschhoff, M., Venkatapathy, A.K.R., Friesel, D., ten Hompel, M., Wietfeld, C., 2017]. PhyNetLab: an IoT-based warehouse testbed. In: 2017 Federated Conference on Computer Science and Information Systems (FedCSIS), IEEE September, pp. 1051–1055.

Gesing, B., Kuckelhaus, M., 2019]. Digital Twins in Logistics. DHL Trend Research.

Giudici, G., Milne, A., Vinogradov, D., 2020]. Cryptocurrencies: market analysis and perspectives. J. Ind. Bus. Econ. 47 (1), 1–18.

Hasan, M., Islam, M.M., Zarif, M.I.I., Hashem, M.M.A., 2019]. Attack and anomaly detection in IoT sensors in IoT sites using machine learning approaches. Internet Things 7, 100059.

He, Z., Aggarwal, V., Nof, S.Y., 2018]. Differentiated service policy in smart warehouse automation. Int. J. Prod. Res., 1–15, http://dx.doi.org/10.1080/00207543.2017.1421789.

Hong-Ying, S., 2009. The application of barcode technology in logistics and warehouse management. IEEE March In: 2009 First International Workshop on Education Technology and Computer Science, Vol. 3, pp. 732–735.

Ingeno, J., 2018]. Software Architect's Handbook: Become a Successful Software Architect by Implementing Effective Architecture Concepts. Packt Publishing Ltd.

Jabbar, S., Khan, M., Silva, B.N., Han, K., 2018]. A REST-based industrial web of things' framework for smart warehousing. J. Supercomput. 74 (9), 4419–4433.

Jaekel, F., 2019]. Systematic review of cloud logistics knowledge. In: Cloud Logistics. Springer Gabler, Wiesbaden, pp. 191–256.

Kamali, A., 2019]. Smart warehouse vs. traditional warehouse–review. Int. J.

Kattepur, A., Rath, H.K., Simha, A., Mukherjee, A., 2018]. Distributed optimization in multi-agent robotics for industry 4.0 warehouses. In: Proceedings of the 33rd Annual ACM Symposium on Applied Computing, April, pp. 808–815.

Köksal, Ö., Tekinerdogan, B., 2017]. Feature-driven domain analysis of session layer protocols of internet of things. In: 2017 IEEE International Congress on Internet of Things (ICIOT), IEEE, June, pp. 105–112.

Kubler, S., Derigent, W., Rondeau, E., Thomas, A., Främling, K., 2013. Embedded data on intelligent products–impact on real-time applications. In: International Conference on Mobile Web and Information Systems, Springer, Cham August, pp. 25–34.

Lam, C.H.Y., Choy, K.L., Ho, G.T.S., Lee, C.K.M., 2014]. An order-picking operations system for managing the batching activities in a warehouse. Int. J. Syst. Sci. 45 (6), 1283–1295, http://dx.doi.org/10.1080/00207721.2012.761461.

Latif, U.K., Shin, S.Y., 2019]. OP-MR: the implementation of order picking based on mixed reality in a smart warehouse. Vis. Comput., 1–10.

Lee, C.K.M., Lv, Y., Ng, K.K.H., Ho, W., Choy, K.L., 2017a]. Design and application of Internet of things-based warehouse management system for smart logistics. Int. J. Prod. Res., 1–16, http://dx.doi.org/10.1080/00207543.2017.1394592.

Lee, Y., Kim, J., Lee, H., Moon, K., 2017b. IoT-based data transmitting system using a UWB and RFID system in smart warehouse. In: 2017 Ninth International Conference on Ubiquitous and Future Networks (ICUFN), IEEE, pp. 545–547.

Leng, J., Yan, D., Liu, Q., Zhang, H., Zhao, G., Wei, L., Chen, X., 2019]. Digital twin-driven joint optimisation of packing and storage assignment in large-scale automated high-rise warehouse product-service system. Int. J. Comput. Integr. Manuf., 1–18.

Li, Z., Li, W., Jiang, L., 2016]. Task assignment problem of robots in a smart warehouse environment. Manag. Stud. 4 (4), 167–175.

Liu, X., Cao, J., Yang, Y., Jiang, S., 2018. CPS-based smart warehouse for industry 4.0: a survey of the underlying technologies. Computers 7 (1), 13.

Lu, Y., Liu, C., Kevin, I., Wang, K., Huang, H., Xu, X., 2020]. Digital Twin-driven smart manufacturing: connotation, reference model, applications and research issues. Robot. Comput. Manuf. 61, 101837.

Martin, R.C., 2000. Design principles and design patterns. Object Mentor 1 (34), 597.

McFarlane, D., Sarma, S., Chirn, J.L., Wong, C.Y., Ashton, K., 2002]. The intelligent product in manufacturing control and management. IFAC Proc. 35 (1), 49–54.

Montreuil, B., 2011]. Toward a Physical Internet: meeting the global logistics sustainability grand challenge. Logist. Res. 3 (2–3), 71–87.

Morariu, C., Morariu, O., Borangiu, T., Sallez, Y., 2013]. Formalized information representation for intelligent products in service-oriented manufacturing. IFAC Proc. 46 (7), 318–323.

Papcun, P., Cabadaj, J., Kajati, E., Romero, D., Landryova, L., Vascak, J., Zolotova, I., 2019]. Augmented reality for humans-robots interaction in dynamic slotting "chaotic storage" smart warehouses. In: IFIP International Conference on Advances in Production Management Systems, Springer, Cham September, pp. 633–641.

Piardi, L., Kalempa, V.C., Limeira, M., de Oliveira, A.S., Leitão, P., 2019]. ARENA—augmented reality to enhanced experimentation in smart warehouses. Sensors 19 (19), 4308.

Qi, Q., Tao, F., 2018]. Digital twin and big data towards smart manufacturing and industry 4.0: 360 degree comparison. IEEE Access 6, 3585–3593.

Reaidy, P.J., Gunasekaran, A., Spalanzani, A., 2014]. Bottom-up approach based on Internet of Things for order fulfillment in a collaborative warehousing environment. Int. J. Prod. Econ. 159, 29–40.

Runeson, P., Höst, M., 2008]. Guidelines for conducting and reporting case study research in software engineering. Empir. Softw. Eng. 14 (2), 131, http://dx.doi.org/10.1007/s10664-008-9102-8.

Sallez, Y., Berger, T., Deneux, D., Trentesaux, D., 2010]. The lifecycle of active and intelligent products: the augmentation concept. Int. J. Comput. Integr. Manuf. 23 (10), 905–924.

Stoltz, M.-H., Giannikas, V., McFarlane, D., Strachan, J., Um, J., Srinivasan, R., 2017]. Augmented reality in warehouse operations: opportunities and barriers. IFAC-PapersOnLine 50 (1), 12979–12984, http://dx.doi.org/10.1016/j.ifacol.2017.08.1807.

Tekinerdogan, B., 2017. Engineering Connected Intelligence: A Socio-Technical Perspective. Wageningen University, Wageningen, The Netherlands.

Tekinerdogan, B., Öztürk, K., 2013. Feature-driven design of SaaS architectures. In: Software Engineering Frameworks for the Cloud Computing Paradigm. Springer, London, pp. 189–212.

Uzun, B., Tekinerdogan, B., 2019]. Architecture conformance analysis using model-based testing: a case study approach. Softw. Pract. Exp. 49 (3), 423–448.

Vermesan, O., Friess, P., Guillemin, P., Gusmeroli, S., Sundmaeker, H., Bassi, A., Eisenhauer, M., 2011]. Internet of things strategic research roadmap. Internet of Things-Global Technological and Societal Trends 1 (2011), 9–52.

Wang, Q., McIntosh, R., Brain, M., 2010]. A new-generation automated warehousing capability. Int. J. Comput. Integr. Manuf. 23 (6), 565–573, http://dx.doi.org/10.1080/09511921003706215.

Wang, Q., Alyahya, S., Bennett, N., Dhakal, H., 2015]. An RFID-enabled automated warehousing system. Int. J. Mater. Mech. Manuf. 3 (4).

Weske, M., 2019]. Business process modelling foundation. In: Business Process Management. Springer, Berlin, Heidelberg, pp. 71–122.

Won, J., Olafsson*, S., 2005]. Joint order batching and order picking in warehouse operations. Int. J. Prod. Res. 43 (7), 1427–1442.

Yao, Z.Q., Zhu, H.J., Du, W.H., 2014]. Design and implementation of automated warehouse monitoring system based on the Internet of Things. Appl. Mech. Mater. 543, 1099–1102, Trans Tech Publications Ltd.

Yongsheng, L., Wenling, Z., 2004]. Warehousing and Distribution Management.

Zhong, R.Y., Xu, C., Chen, C., Huang, G.Q., 2017]. Big data analytics for physical internet-based intelligent manufacturing shop floors. Int. J. Prod. Res. 55 (9), 2610–2621.

Zhou, W., Piramuthu, S., Chu, F., Chu, C., 2017]. RFID-enabled flexible warehousing. Decis. Support Syst. 98, 99–112, http://dx.doi.org/10.1016/j.dss.2017.05.002.

Žunić, E., Delalić, S., Hodžić, K., Beširević, A., Hindija, H., 2018. Smart warehouse management system concept with implementation. In: 2018 14th Symposium on Neural Networks and Applications (NEUREL), IEEE November, pp. 1–5.