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Use of a wireless sensor system to monitor the transport of goods

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Abstract

With about one third of all food wasted, food loss is a global problem. It occurs in all supply chain phases, with transportation accounting for a large share of spoilage. Wireless sensor networks can be used to monitor transportation processes and counteract these losses. This thesis addresses the requirements and explores the challenges of such systems. Important aspects are the deployment, communication and power supply of the sensor system. Additionally, a cost-benefit analysis has been conducted to assess the economic value of transportation monitoring systems.

Keywords

Cost-Benefit Analysis, Internet of Things, Perishable Goods, Requirements Engineering, Transportation Monitoring, Wireless Sensor Network

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Finally, I would like to express my gratitude to my family and friends for the mental support and continuous encouragement throughout the previous years of studying and writing this thesis. Thank you.

Terminology

2G, 3G, 4G	2nd, 3rd and 4th generation of mobile network technology
6LoWPAN	*IPv6 over Low-Power Wireless Personal Area Networks* Allows IPv6 packets to be transmitted over the IEEE 802.15.4 standard
CBA	*Cost-benefit analysis*
CoAP	*Constrained Application Protocol* Specialized web transfer protocol for constrained devices
container level	In this report referred to as monitoring of the entire cargo container
CPU	*Central processing unit*
EPC	*Electronic Product Code* part of RFID tag memory
GPS	*Global Positioning System*
HTTP	*Hypertext Transfer Protocol* Protocol on application layer for transmitting hypermedia documents
I^2C	*Inter-integrated circuit* Synchronous serial communication commonly used by microcontrollers
IEEE	*Institute of Electrical and Electronics Engineers*
Intermodal transportation	Transportation process that involves the transportation of goods in one container, which is used on multiple transportation modes.
ISM	*Industrial, scientific and medical radio band* Generally license-free frequency bands for industrial, scientific and medical purposes
item level	In this report referred to as monitoring of single items or transport boxes
LAN	*Local Area Network*
LF	*low frequency* radio frequencies from 30 kHz to 300 kHz
pallet level	In this report referred to as monitoring of pallets
PAN	*Personal Area Network*
PPS	*Piezoelectric power supply* Using the piezoelectric effect as power supply
RCM	*Remote Container Management* Maersk's monitoring system
Reefer container	Refrigerated shipping container that is used in intermodal transportation
RFID	*Radio Frequency Identification* Use of electromagnet fields to read and capture information stored on tags
RTC	*Real-time clock* integrated circuit keeping track of the current time
SPI	*Serial Peripheral Interface* synchronous serial communication commonly used by microcontrollers

TID	*Tag Identifier* part of RFID tag memory
UHF	*ultra-high frequency* radio frequencies from 300 MHz to 3 GHz
URI	*Uniform Resource Identifier*
WAN	*Wide Area Network*
WLAN	*Wireless Local Area Network*
WSN	*Wireless Sensor Network*

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1 Introduction

About one third of fresh fruits and vegetables are wasted globally due to insufficient quality. There are several factors adding up to this number. Reasons are manyfold, such as overproduction, consumers buy more than they use, and several factors affecting the goods during storage and transportation. Food losses in the cold chain alone account for 5 to 25% of products being lost. And this is not only true for farm produce. Other perishable products are affected, too (Jedermann, Nicometo, Uysal, & Lang, 2014).

There are different factors that affect the shelf life of perishable goods during transportation over long distances, such as temperature, humidity, shock and vibration, ethylene concentration, $C0_2$ and O_2 concentration (Jedermann, Nicometo, et al., 2014).

One possible solution to counteract these high losses is the use of modern technologies to monitor these quantities. The idea is to equip transport boxes or containers with sensors that measure relevant parameters frequently and notify stakeholders about improper conditions, so actions can be taken in order to improve the situation.

This can be done with a wireless sensor system, in which sensors either communicate directly over the internet or send data to a communication module, which then forwards the data to a web server. An online platform can be used to set up new sensor devices and connect them to a specific consignment. Furthermore, it can be used to monitor the measured parameters in real-time and thus, have an overview of the goods' condition at any time. By specifying appropriate limits, in which values can vary, the online platform can automatically inform various stakeholders as soon as values are not within these limits. In this way, drivers, logistics workers, and other stakeholders can react immediately.

1.1 Problem formulation

This project addresses technological and business-related aspects of transportation monitoring systems. The main objective of the Master thesis project is to examine the requirements, costs and benefits of a wireless sensor system for monitoring the transport of perishable and easily damageable goods, such as food and pharmaceuticals. Part of the project will be the development of a concept of such system. Thus, the following question is raised:

What are the requirements, costs and benefits of monitoring the transport of goods with help of a wireless sensor system?

In order to answer this question successfully, it is important to consider several aspects, including:

- Design and deployment of sensor system
- Communication of sensor system
- Power supply of sensor nodes
- Costs and benefits for all stakeholders

1.2 Thesis outline

The remainder of the thesis is structured as follows. Section 2 describes the methodology applied in this project. This includes the methods used for data collection and the way the requirements engineering process and cost-benefit analysis is conducted. Section 3 describes the state of the art in supply chain management, wireless sensor networks, monitoring systems for the logistics industry, requirements engineering, as well as cost-benefit analysis. Thereafter, in section 4, the information collected through the interviews as well as the literature review are presented. In section 5, this data is analyzed according to the points described in the previous subsection. Section 6 describes the development of the proof of concept. In section 7 and 8, the results of the analysis are discussed, and the paper is ended with final conclusions.

2 Methodology

The requirements and benefits of a wireless sensor system for monitoring the transportation of goods will be investigated mainly by literature review and state-of-the-art analysis, taking into account existing monitoring systems and research in the field of *Internet of Things* and *wireless sensor networks*.

Additionally, interviews are conducted with logistics companies in order to find out how goods are specifically transported throughout the supply chain and what challenges they face.

Furthermore, a proof of concept shall be developed in order to demonstrate the practical potential of such a system.

2.1 Data collection

For the assessment of state-of-the-art monitoring systems for the transportation industry, literature in this field has been reviewed over the course of this project. It is the main input of information and serves as the basis for the results. The used literature has been found with the help of a search protocol, which can be found in Appendix A. The main source is the platform *Engineering Village*, which uses among others the database *Compendex*.

Moreover, primary data was collected by interviewing responsible employees of logistics companies, in order to understand how goods are specifically transported by these companies, what challenges they face, as well as their current approach to monitoring the goods in transit. Around 20 companies were contacted. Unfortunately, most companies were not interested in an interview or simply could not allocate time. An interview was conducted with three companies: Kuehne+Nagel, Scan Global Logistics, and Freja Transport & Logistics. Summaries of the interviews can be found in Appendix B.

2.2 Requirements Engineering

The requirements engineering process used in this project is based on the process described in chapter 3.4.

For data acquisition, the interviews are used as primary data and the literature review of monitoring systems as secondary data. The levels of requirements addressed in this report comprise the statements of needs, system requirements and system component requirements (cf. chapter 3.4.4). The statements of needs are the basic requirements, or needs, expressed in the interviews and in literature. The system requirements are the next lower level requirements, derived from the statements of needs. These requirements address the system as a whole, in terms of used technologies and installation of the system. The system component requirements are derived from the system requirements. They address the components of the system in its own entities, such as sensor nodes and gateway nodes in the wireless sensor network.

As described in chapter 3.4.4, engineering requirements is a four-step process. It consists of assessing the input requirements in terms of completeness and clarity. Thereafter, the requirements are analyzed, which involves comparing different solutions based on existing and proposed systems. This results in a set of derived, lower level requirements, which has to be assessed again: all input requirements have to be satisfied and each derived requirement has to satisfy at least one input requirement.

2.3 Cost-benefit analysis

The purpose of the cost-benefit analysis in this project is mainly to get an overview of costs and benefits of a wireless sensor network for transportation monitoring, as well as to compare it with existing solutions in the industry. The conducted analysis is based on a specific scenario.

The process of the analysis is based on the cost-benefit analysis described in chapter 3.5, which describes a process for a general cost-benefit analysis mainly used by governments to assess the advantages and disadvantages of a certain project and determine whether it is beneficial for the society. The cost-benefit analysis methodology has been adapted to the project described in this report. The following steps have been taken to conduct the analysis.

1. **Specify alternative projects.**

Two alternatives have been specified that can be compared to each other and to the option of not implementing a monitoring system. One alternative is a monitoring system according to the requirements in chapter 5.1. The second alternative is an example of a monitoring system that is used in the industry today.

2. **Determine the stakeholders whose costs and benefits should be taken into account.**

The second step does also not differ from the original methodology and comprises the definition of stakeholders, whose costs and benefits are considered in the analysis.

3. **List the costs and benefits.**

All impacts (costs and benefits) of all determined stakeholders are described and listed. Furthermore, the impacts are categorized for a clearer overview.

4. **Quantify costs and benefits and assign a monetary value to the impacts.**

In order to quantify costs and benefits, a specific scenario has been chosen, which is described in chapter 5.2.4. In this way, quantitative data could be gathered about certain factors affecting the costs and benefits listed before. Based on specific assumptions, the costs and benefits are quantified, and a monetary value is assigned. As opposed to the original cost-benefit analysis, the costs and benefits are not quantified over the entire life of the project because it depends on a lot of different factors, such as the adoption of the systems and the specific consignments. Therefore, the costs and benefits are quantified for the specified scenario that covers the duration of one consignment.

5. **Calculate the net benefit of each alternative.**

The net benefit is calculated by subtracting all costs from all benefits. This is done for each alternative and thus, the alternatives could be compared. A positive net benefit means that the alternative is beneficial compared to not implementing any alternative. The higher the net benefit, the higher the potential of an alternative to having a positive impact.

3 State of the art

The goal of this chapter is to establish the basis of research about supply chain management, state-of-the-art solutions for transport monitoring systems and wireless sensor network technologies. There are several research projects about real-time monitoring of goods. However, many of them are only concepts and not fully functional solutions that are available on the market. The focus of this chapter will be to find out what technologies were used in the examined solutions, how the system is deployed, and what challenges of implementation were faced.

3.1 Supply chain management

Supply chain management is often understood in different ways, depending on who gives the explanation. In fact, it covers several entities and processes from designing new products to the delivery of these products to end customers (see Figure 1). It is the management of this complete process, that includes „product design, procurement, planning and forecasting, production, distribution, fulfillment, and after-sales support“ (Lu & Swaminathan, 2015).

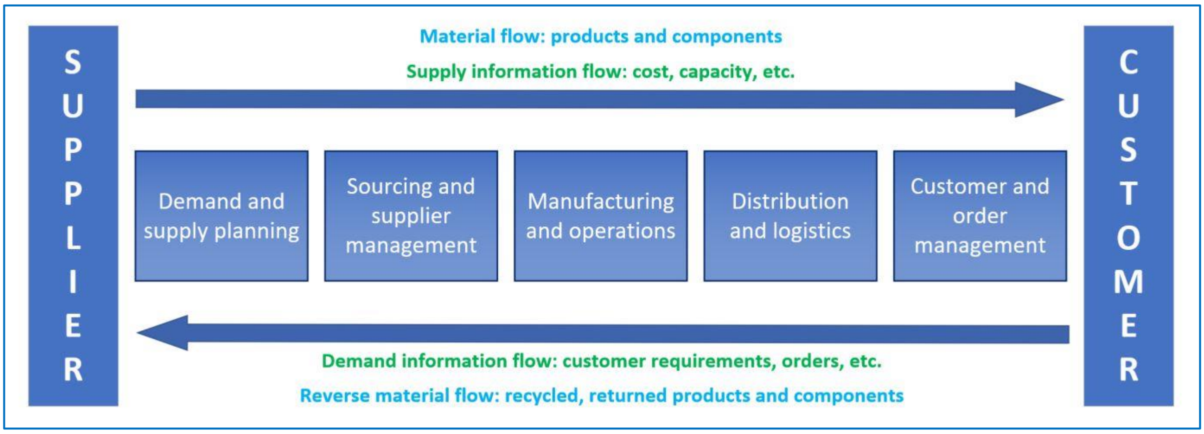

Figure 1 - Supply chain process

While supply chain management focuses on many different aspects, this report mainly focuses on the transport and logistics of products from the supplier to the retailer. The following subchapters are about the supply chain of food products and forms of transportation, specifically for the food industry as food is the major category of perishable goods. However, the theory can also be applied to other industries.

3.1.1 Supply chain of food products

The food supply chain covers a variety of different products, from fresh produce, animal products and meat, dry goods, convenience products, etc. As depicted in Figure 2, it comprises three main sectors: agricultural sector, food processing sector, and the distribution sector. The origin of generally all food products is the agricultural sector. The distribution channels are very diverse due to the variety of different products. Products are sold from the agricultural sector to the food processing sector, the distribution sector, alternative markets, or directly to the consumer (Bukeviciute, Dierx, & Ilzkovitz, 2009). Except of the latter, it is generally being sold by wholesale. After being processed in food processing businesses, food is transported to the distribution sectors, which covers businesses such as retail stores and restaurants. These businesses are primarily selling the food to consumers.

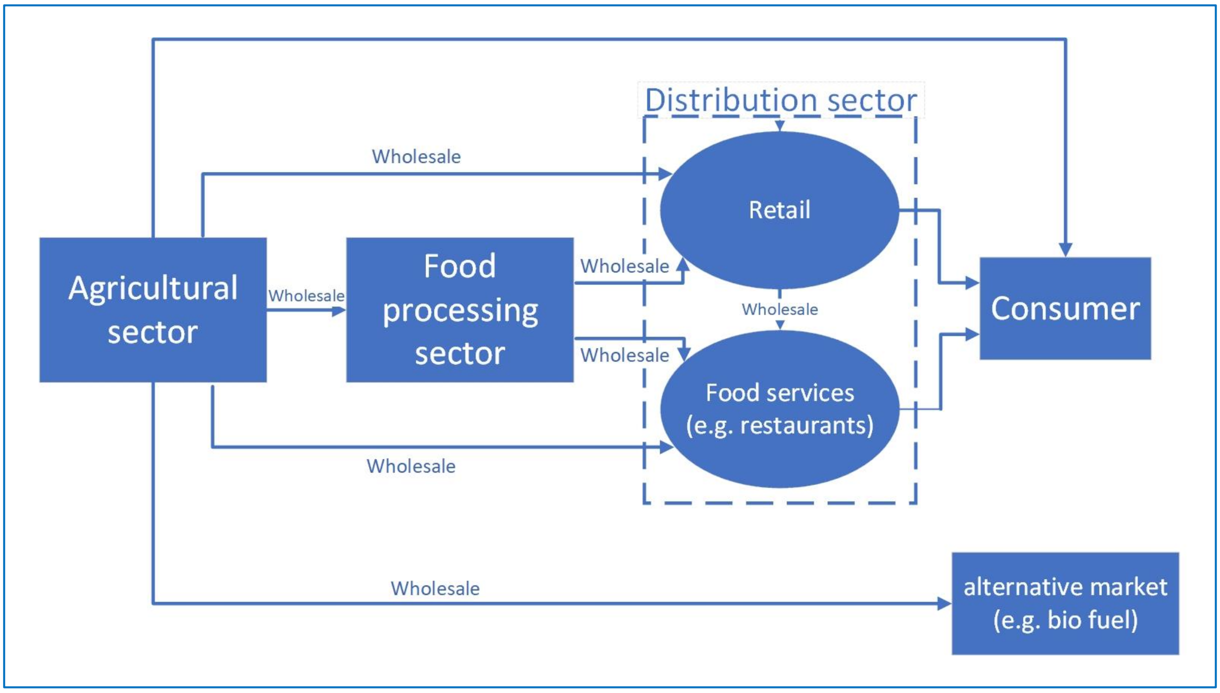

Figure 2 - Food supply chain

3.1.2 Forms of transportation

The forms of transportation can be divided into three categories: air, sea, and land transportation. Air transportation is often used for valuable, perishable goods, such as high-quality meat products and pharmaceuticals. It is a very fast method of transporting goods over long distances. However, the products are often not actively refrigerated during transport. They are often just carried in standardized containers that are insulated and provided with dry ice without temperature control (James, James, & Evans, 2006).

Sea transportation can take multiple weeks and thus, it is required to preserve the food products on the long journey. Containers have most often an integrated refrigeration unit that allows a temperature-controlled transport. These containers are often called reefer containers. Due to the air transfer, reefer containers often have to be carried on deck as opposed to cargo holds, where it is more difficult to control the temperature due to sunlight and weather conditions. However, depending on how the goods are loaded into the container, product temperatures can be retained within ±1 °C of the controlled temperature (James et al., 2006).

Long distance overland transportation takes place on the road or by rail, where active refrigeration is used as well. However, the last stage of transportation to retail stores or directly to the consumer is often done with small vans that are not actively cooled (James et al., 2006).

The transport of containers has increased significantly in the recent years and the use of intermodal containers is commonly adopted. Intermodal containers are containers that can be used on different forms of transportation. Therefore, when changing means of transportation, goods don't have to be handled directly but only the containers have to be loaded and unloaded, thus making transportation more efficient (Crainic & Kim, 2007).

Generally, fresh products are packed into transport boxes on the producer's site, where these boxes are also loaded into the container. Depending on the product type, different types of boxes are used, e.g. cardboard boxes for bananas (Heisselberg, 2018). When temperature control is necessary, reefer containers are used. These containers are equipped with a mechanical compressor, so the air inside the container can be cooled or heated. The air is usually supplied from the bottom and the floor has grooves that ensures air can flow throughout the entire container. However, the loading and packaging of the goods is an important aspect of successful transportation (Kuehne+Nagel, n.d.). In fact, one major reason of spoiled goods during transportation is improper packing and loading (Heisselberg, 2018). Other parameters beside temperature that can be controlled are relative humidity, supply of fresh air and controlling of carbon dioxide and oxygen levels. Regarding the power supply, the reefer containers are connected to the power supply on the ship during sea transportation. However, an external diesel generator is often used during land transport (Kuehne+Nagel, n.d.).

3.2 Wireless sensor networks

A wireless sensor networks (WSN) usually refers to a network that consists of several sensors monitoring various physical or environmental conditions and communicating the data wirelessly. A sensor device generally comprises different modules that allows the device to sense, process and communicate (K M, 2017). Looking at the information value loop in Figure 3, information is created, communicated, and aggregated by a wireless sensor network. Analyzing usually happens at a central location and acting can only be performed automatically if actuators are implemented into the system.

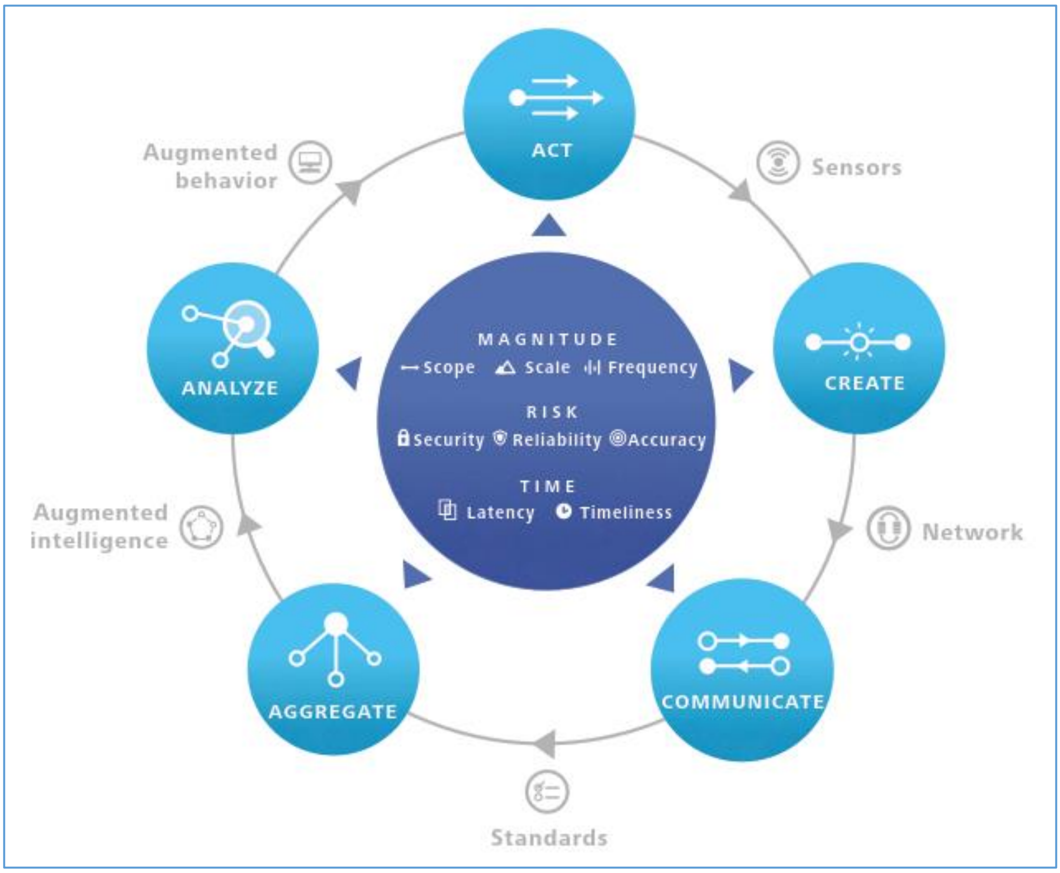

Figure 3 - Information Value Loop (Holdowsky, Mahto, Raynor, & Cotteleer, 2015)

3.2.1 Sensor node architecture

A sensor node is responsible for at least creating and communicating information. Therefore, as shown in Figure 4, it consists of different components in order to reliably perform these actions, such as:

- Sensor unit(s)
- Processing unit
- Communication unit
- Power supply

Sensor unit

A sensor unit is the actual sensor that senses the physical parameter, such as temperature or humidity and converts it into an electrical signal. A wireless sensor node can contain multiple sensor nodes that are all connected to the IO pins of the processing unit. In this way, a node can sense various physical parameters. Selecting a specific sensor depends on several factors, including the accuracy, repeatability, range, and resolution (Holdowsky et al., 2015). Thus, the accuracy of a node is determined by the choice of the sensor(s). Various sensors on the market already come with integrated analog-to-digital converters and are able to communicate via communication protocols commonly supported by microcontrollers, such as SPI or I^2C.

Processing unit

The processing unit is a microcontroller that acts as an intermediary. It receives data from the sensor unit(s), possibly processes the data, and forwards it to the communication unit. As wireless sensor nodes are usually battery-powered, one of the biggest challenges is to reduce the power consumption. Hence, the processing unit is also responsible for power management functions. The communication unit generally uses the most power. The power usage can for example be limited by only transmitting data when the value of the physical parameter changes or by lowering the transmission frequentness. Furthermore, sleep modes can be implemented in order to put the node into a very low power state in between measurements (Wilson, 2004). The processing unit incorporates the intelligence so to speak and manages the other units and the flow of data within the node.

Communication unit

The communication unit consists of a radio frequency transmitter or transceiver, depending on whether it is required to also receive data or only send data. It is responsible for communicating to other nodes in the network. The choice of a specific radio frequency integrated circuit depends on which network technology is used and the requirements of the WSN. There are various network technologies, suitable for different uses, geographical ranges, power requirements, required data rates, and so forth. Examples for short ranges (up to a few meters), usually referred to as personal area network (PAN) technologies are ZigBee, 6LoWPAN, and Bluetooth. Examples for Local area network (LAN) technologies for medium ranges (e.g. inside or across buildings) are the IEEE 802.11 standards, which WiFi is based on. Wide area network (WAN) technologies are for very long distances and examples are cellular technologies, such as 3G or 4G (Holdowsky et al., 2015; Shelby & Bormann, 2009; Wilson, 2004). Relevant technologies are described more specifically in chapter 3.2.3.

Power supply

The sensor nodes need to be powered in some way. Whereas external power supply, e.g. directly from the power grid or from the car battery, provides almost constant power supply, it is less flexible and often not possible for many applications. Powering sensor nodes with individual batteries however, induce issues regarding the battery life and the replacement of batteries (Holdowsky et al., 2015). Especially for battery-powered devices, it is important to use low power network technologies and take power saving strategies into account.

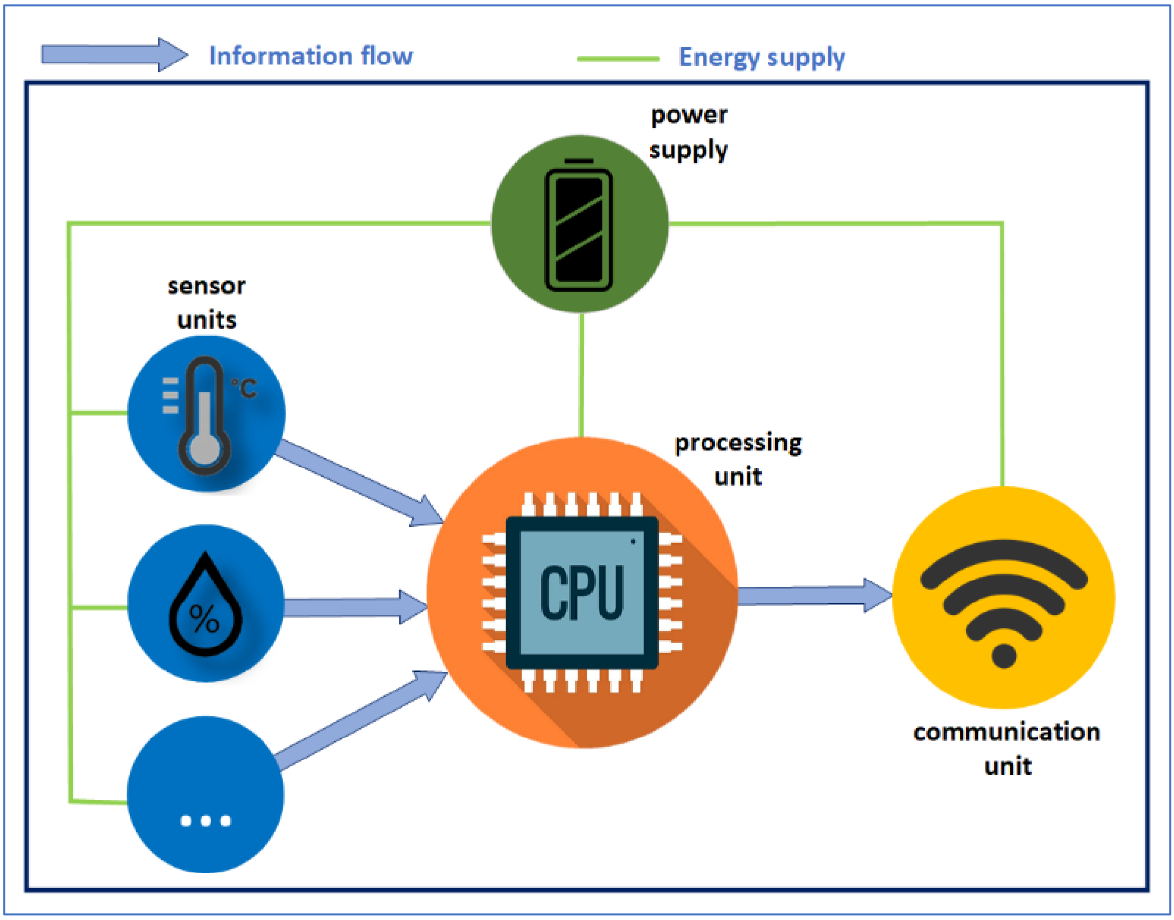

Figure 4 - Sensor node architecture

3.2.2 Network topologies

The network topology indicates how the nodes of a network are arranged and linked together. The most common topologies used for WSNs are star or mesh topology, or a combination of both as shown in Figure 5. In general, a wireless sensor network contains of several nodes and a central node, such as a gateway, that can interface with another network, e.g. transmitting the data of multiple sensors in a low power PAN over a large distance requires a gateway to communicate beyond the boundaries of the PAN.

Star topology

In a star topology, all sensor nodes are directly linked to the central node. Sensor nodes cannot communicate with each other, but only with the central node. This keeps the network very simple and the power consumption for sensor nodes low. However, all sensor nodes have to be within range of the central node.

Mesh topology

In a mesh network, all nodes can communicate with each other as long as they are within the transmission range. Thus, multi-hop routing is possible, which means that nodes can be used as intermediaries that forward the data to the next node, until it reaches the central node. This type of network is more complex, but it provides the advantage that the coverage of the entire network can be larger than the transmission range of a single node. Thus, the network can be larger than with a star topology or the transmission power can be reduced for having the same range, which reduces the power consumption of a single transmission. On the other hand, data is transmitted more often over multiple hops and thus may increase the total energy consumption. Research shows that advantages in energy consumption of multi-hop routing over single-hop routing depends on how the nodes are aligned in the network (Fedor & Collier, 2007).

Hybrid topology

A hybrid star-mesh topology is the combination of both types. Several sensor nodes are only able to communicate to one intermediary node, thus having a star topology. These intermediary nodes generally require more power and communicate with other intermediary nodes in a mesh topology, forwarding the data until it reaches the central node (K M, 2017; Wilson, 2004).

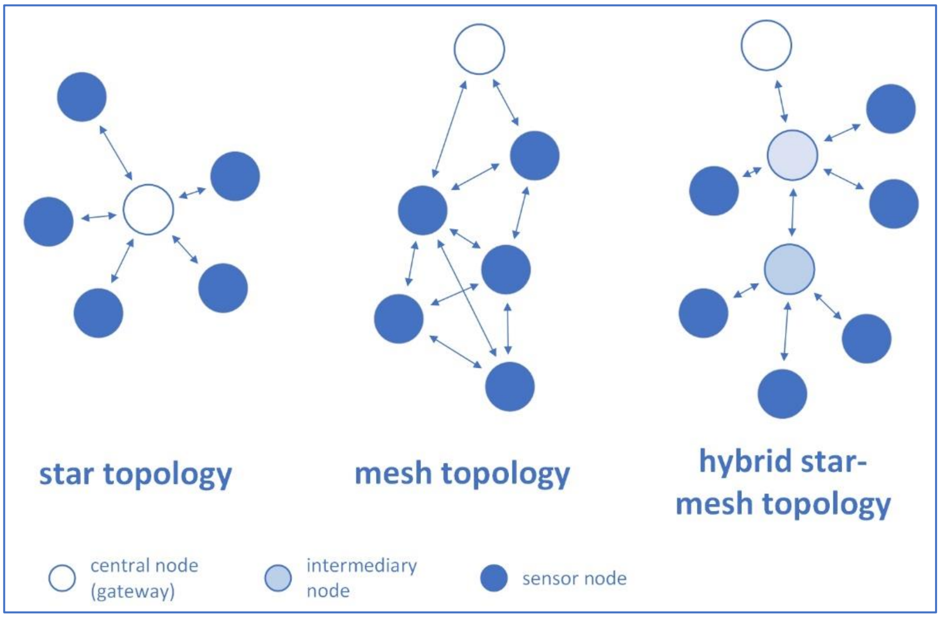

Figure 5 - Wireless sensor network topologies

3.2.3 Communication technologies

This chapter will describe several state-of-the-art wireless communication technologies that are suitable for sensor networks, such as Zigbee, 6LoWPAN and RFID.

IEEE 802.15.4

The IEEE 802.15.4 is a network technology standard for wireless personal area networks with a focus on low cost and low data rate applications. Therefore, the target is sensor and automation-related implementations. Even though there are three different frequency bandwidths defined, most implementations today use the widely-used 2.4 GHz bandwidth. In the standard, the physical layer and media access control layer (part of data link layer as defined by IEEE 802) are defined and it forms the basis for ZigBee and 6LoWPAN, among other higher level standards (Hersent, Boswarthick, & Elloumi, 2012).

ZigBee

ZigBee uses the 2.4 GHz bandwidth of the ISM band and can therefore be used license-free. The standard defines several protocol layers, so for example the network layer that adds mesh routing functionality to the 802.15.4 standard, as well as network management functionality. The next higher layer that is defined is the application support layer. It serves several purposes, such as implementing security mechanisms, forwarding of network layer messages to the right application nodes, and fragmentation mechanisms (Hersent et al., 2012; Tennina et al., 2013).

The ZigBee standard defines three different type of nodes that a network can exist in the network:

- *ZigBee End Device*: it is simply an end node that is not responsible for routing message and therefore not actively listening. It could be a sensor node that is periodically measuring parameters and transmitting the information and stays the rest of the time in sleep mode.
- *ZigBee Router*: this node is actively listening because it has to forward message from other nodes in a multi-hop network.
- *ZigBee Coordinator*: the coordinator is responsible for initiating and forming the network. It often functions as a gateway to other networks.

These types are not mutually exclusive, which means that one device can implement the functionality of multiple types, e.g. the ZigBee coordinator functions as a ZigBee router as soon as the network is formed (Hersent et al., 2012; Tennina et al., 2013).

Regarding the power consumption, ZigBee transceivers are very economical. As end devices are usually in sleep mode most of the time, ZigBee transceivers can run on an AAA battery for a year (Ghosh, 2017).

One drawback of the ZigBee standard is that it does not implement functionality for the seamless integration with IP-based networks and thus, complex gateways need to be used (Ghosh, 2017).

6LoWPAN

The goal of 6LoWPAN (IPv6 over low-power wireless personal area networks) is to go one step further and utilize IP technology over the IEEE 802.15.4 standard and thus enable the connection of sensor devices to the internet. The motivation is to combine the advantages of the IEEE 802.15.4 standard, such as low energy operation, with IP-based networks (Ghosh, 2017).

The issues are that IPv6 packets are usually quite large (up to 1280 bytes) and have a much bigger overhead. The header alone is 40 bytes while IEEE 802.15.4 supports packet sizes of 127 bytes. Therefore, 6LoWPAN supports header compression, as well as fragmentation and reassembly mechanisms to break up the large IP packets, so that it can fit into IEEE 802.15.4 packets (Ghosh, 2017; Minoli, 2013).

RFID

Radio frequency identification (RFID) is the use of electromagnetic fields for the purpose of identifying objects that are equipped with RFID tags. These tags, e.g. in the form of a card, have an integrated antenna and microchip. With passive RFID, an external reader sends out an electromagnetic signal that is received by the antenna of the passive tag. This tag uses the energy of the incoming signal to send out another electromagnetic signal, containing the data stored in the tag. The external reader receives this signal and decodes the information to identify the tag, and possibly gather other information on the tag (Piramuthu & Zhou, 2016). The working principle of RFID is shown in Figure 6 below.

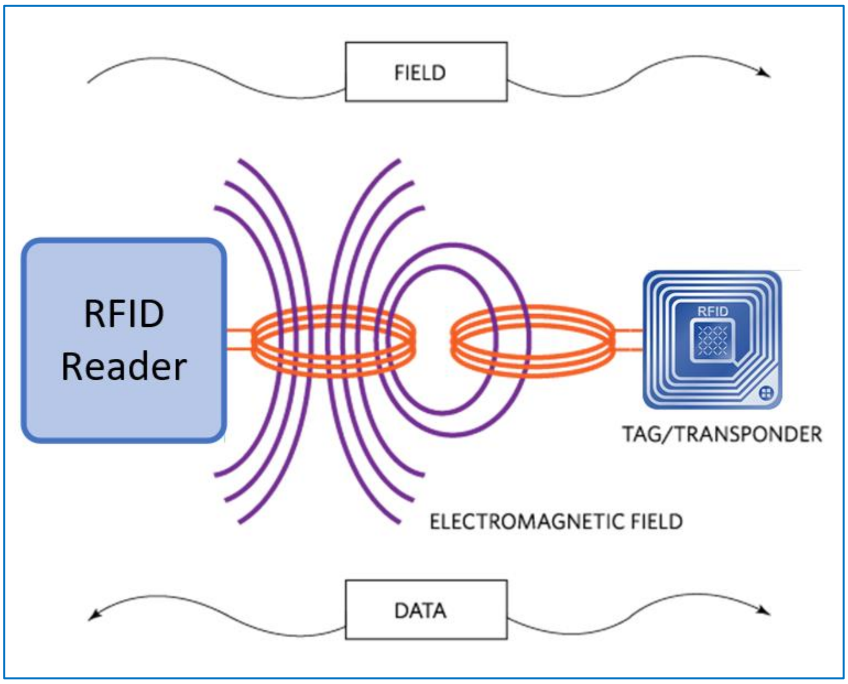

Figure 6 - RFID principle

There are generally three categories of RFID tags: passive tags, active tags, and semi-passive (or semi-active) tags. A passive tag does not have its own energy supply and is powered by the RFID reader as it is explained above. It can only store information and transmit them to the reader when receiving an electromagnetic field. It is incapable of performing other tasks. An active tag has its own power source and is usually capable of performing other tasks, such as sensor measurements. It does not need the readers electromagnetic field to transmit data. A semi-passive tag functions like an active tag, so it can also perform other tasks because it is supplied by its own power supply. However, for transmitting data, it uses the energy of the electromagnetic field of the reader, like a passive tag does. The range for active tags can be much larger than for (semi-)passive tags and in general ranges from a few centimeters to over 100 meters (M. Chen & Chen, 2016; Y. Li, Deng, & Bertino, 2013).

There are several operating frequencies for RFID, such as LF RFID (120 to 140 kHz), HF RFID (13.56 MHz), and UHF RFID (868 to 928 MHz). Passive UHF tags have generally the lowest costs and prices are as low as $0.1. However, they do not work reliably close to metallic and liquid substances (Advanced Mobile Group, 2016; Sen, Sen, & Das, 2009; Weis, 2007).

It is important to note that RFID is not bound to any specific wireless communication or networking technology, but it rather describes the identification of tags by using radio signals. Active RFID can for instance be achieved by using ZigBee as the networking technology.

3.3 Logistics monitoring systems

Wireless sensor networks can be used to monitor goods during the transportation process. This chapter describes several proposed or existing monitoring systems for this industry. The systems described here cover monitoring systems used in the industry as well as proposed in research projects, found through the literature review (see Appendix A). The literature review is based on the search protocol described in Appendix A. Industrially deployed systems can hardly be found, and especially technical information is most often not publicly available. Therefore, the focus is on proposed systems based on scientific research.

3.3.1 The Intelligent Container

The Intelligent Container is a project, run by a consortium of 21 partners from research and industry and financed by the German Federal Ministry for Education and Research. The objectives of the project were autonomously monitoring the quality of food and reducing the loss of food during transport, developing shelf life models in order to predict changes in the quality, and implementing a prototype as well as testing the intelligent container.

Models were created that helped to predict the shelf life of a product. Two types of food were selected to conduct detailed analyses, bananas and meat products. For meat products, the main parameter is temperature that needs to be taken into account in order to estimate the shelf life. Results showed for bananas that besides temperature, other parameters that affect the shelf life were air humidity and the composition of the atmosphere, such as CO_2 or ethylene concentration, a gas that is emitted by bananas and other fruits during the ripening process.

Further results showed that the temperature had to be measured inside transport boxes in order to accurately predict the shelf life of the goods. One container required about 10 to 20 sensors because of temperature deviations inside.

One challenge was the attenuation of signals sent by the wireless sensors due to the high water content of food products. In order to make the communication work reliably, the messages needed to be forwarded from sensor to sensor. Therefore, standardized communication protocols were used so that sensors of different manufacturers can be used. As sensor nodes are resource-constrained in regards, such as power consumption, the sensor network is based on an 6LoWPAN network, a lower power personal area network that is suited for IoT applications. The communication was based on CoAP, the *Constrained Application Protocol*, which is compatible with HTTP but kept simple and with low overhead and therefore suitable for constrained devices in IoT applications, as well as 6LoWPAN (Institute for Microsensors -actuators and -systems (IMSAS), n.d.). Figure 7 shows the system architecture of the intelligent container.

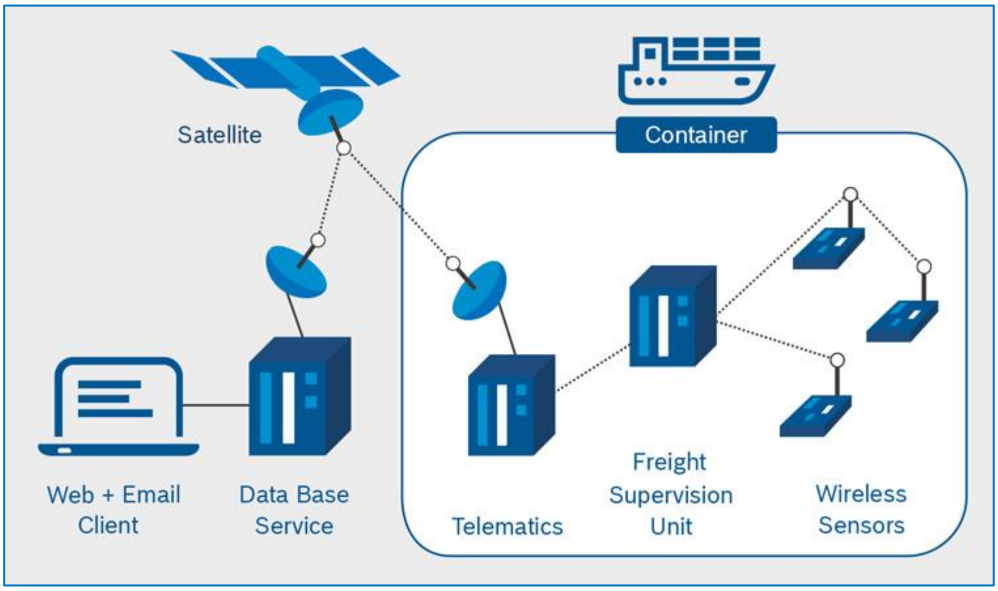

Figure 7 - Intelligent container, system architecture (Pursche, 2016)

The wireless sensor node consists of several components that enables the measurement of environmental conditions and the transmission of these signals to the base station. A requirement was a low-power implementation. Therefore, a low-power microcontroller from the company ARM is used, that is very energy-efficient but has enough computing power for implementing shelf life models directly in the sensor node. In the basic version, a combined humidity and temperature sensor is used as the sensor unit. The communication module is a UHF transceiver, which is used for the data transmission.

The communication module required the largest share of the total power consumption. In order to prevent the battery from draining too fast, a wake-up mechanism was implemented. A LF semi-passive RFID receiver is used to wake up the node if a request is sent from the base station.

Moreover, the signal strength of the wake-up signal was measured in each of the three spatial axes, which was supposed to give an indication about the position of the sensor node inside container. However, this was not very accurate due to varying values because of an inconstant voltage of the battery (Heidmann et al., 2013).

3.3.2 Development of wireless sensor network for temperature monitoring

In a collaboration between the Taiwanese Industrial Technology Research Institute and the National Chiao Tung University, another wireless sensor network for temperature monitoring has been presented. The focus was on the link quality inside the container.

The wireless sensor network has a 3-layered approach, similar to other systems. The sensing layer consists of several wireless sensor nodes. An experiment was conducted with 105 sensor nodes, each attached to a transport box. Each node consists of the low-power microcontroller *Jennic JN5148* that includes a 2.4 GHz transceiver, compatible to IEEE 802.15.4., which is the basis for ZigBee or 6LoWPAN communication. Furthermore, a thermocouple with A/D converter, a real-time clock and a logic detector are part of the sensor node. The logic detector is connected to the A/D converter and used to wake-up the microcontroller, if the temperature is beyond set limits. The sensor nodes send the measured data to an access point (AP), which integrates a GPS and 3G communication module, so the data can be sent to a remote server.

The paper describes the problem of attenuation inside the container. Especially food products contain a lot of water, which absorbs microwave signals. This is a big challenge in monitoring goods. Therefore, the paper describes an experiment in which the link quality is tested by using 105 water-filled styrofoam boxes, which are stacked in seven vertical layers of 3 x 5 inside a standard 20-foot container, as illustrated in Figure 8.

The experiment was conducted three times, each with a different position of the AP in order to see where the best link quality is among all the sensor nodes. For each of the three cases, a star topology was chosen. Due to the attenuation, the sensor nodes were located on the outside of the boxes, whereas the thermocouple was inserted into the box through a small hole. There was a gap of 8 cm between each vertical layer A to G (see Figure 8).

The results showed that in all three cases, a reading efficiency of over 95% could be obtained, which allows a well-functioning WSN, while keeping the power consumption to 50 mW when transmitting, and 59 mW when receiving respectively (C.-M. Li, Nien, Liao, & Tseng, 2012).

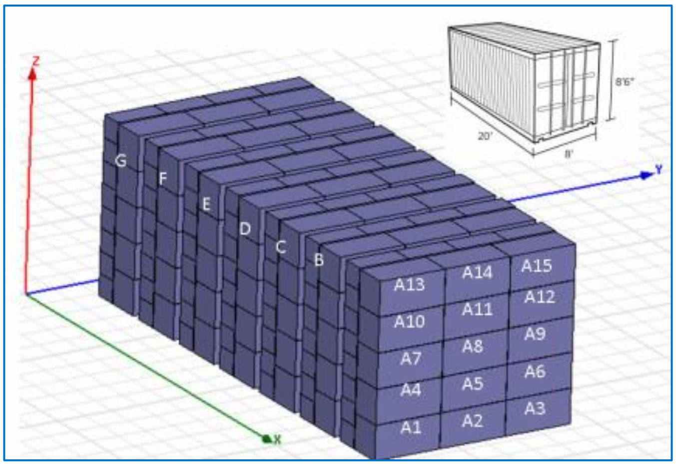

Figure 8 - Wireless sensor network, link quality experiment

3.3.3 Smart cold chain system using 2G-RFID

Published by researchers of the National Chung Hsing University, the smart cold chain system using 2G-RFID is a paper proposing a monitoring system for the cold chain by the use of passive RFID tags. It is intended to be used during storage, transport, and retail of perishable food products. A similar project using semi-passive RFID tags has been proposed earlier. The intention of the new project is to lower the costs, both the initial investment and operational cost.

The system comprises four sub-systems: an information system, a middleware including RFID reader, a sensor and control device, and several RFID tags. The system architecture is depicted in Figure 9.

The information system is, like in many other monitoring systems, a remote server with a database that stores all data and allows remote monitoring of the conditions inside the container.

The RFID tags are attached to transport boxes and contain various data about the goods that it is attached to, such as storing conditions, expiry date, and instructions what to do when storing conditions are not met. This information is described as the mobile code. As these tags don't measure anything and simply store information, passive tags are used, meaning they don't need a power source, making them cheaper in purchase and operation. RFID tags contain three different types of memory. Besides the tag identifier (TID), there is the electronic product code (EPC) and the user memory. While the TID uniquely identifies the tag, the EPC should be used to identify the object, that the tag is attached to (Traub, 2016). The user memory can contain any information about the object. In this research project, it is the so-called mobile code.

The sensor and control device measures atmospheric conditions, such as temperature, humidity, and pressure. Furthermore, it can control various parameters, such as the temperature and the power to the system.

The middleware functions as a coordinator between the other components. It consists of an RFID reader, so that it can read and store the information of the RFID tags and act accordingly by sending commands to sensor and control device. It also receives the measured data from the sensor & control device. Moreover, it transmits the data to the remote information system.

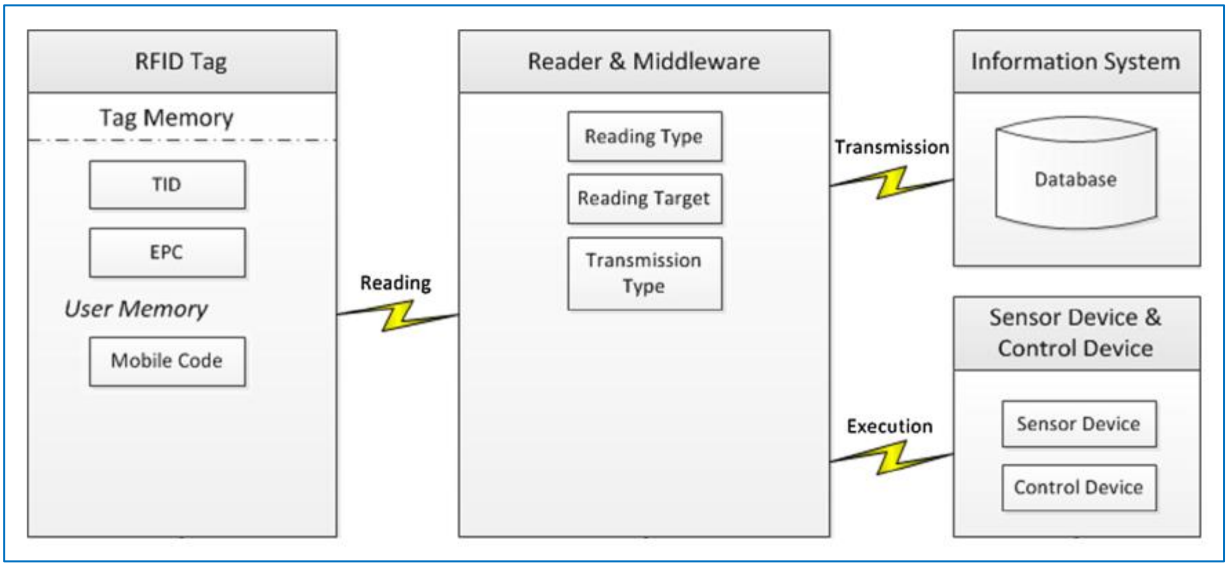

Figure 9 - 2G-RFID smart cold chain system architecture (Y.-Y. Chen, Wang, & Jan, 2014)

The way the system works is that the middleware knows by reading the RFID tags what conditions the control system of the container should provide. This information is sent to the control device. If for instance the temperature, measured by the sensor device, exceed the temperature limits that are stored in the RFID tags, the middleware can react. For example, a tag could contain the instruction to send an alert to the office if the temperature is too high. The middleware will execute this instruction and send an alert.

Compared to the use of semi-passive tags, temperature fluctuations inside the container cannot be measured. However, passive tags are many times cheaper. Furthermore, semi-passive should be reused and tags operate on batteries that must be replaced, which both incurs labor costs (Y.-Y. Chen et al., 2014).

3.3.4 Intelligent tracking system for cold chain based on IoT

Another concept of an intelligent tracking system for the cold chain was proposed in a paper by several researches of two Chinese and one US American university (Luo et al., 2016). The purpose was to monitor real-time temperature, humidity, and geographic location of perishable goods, in the cold chain during storage and transportation.

The proposed system has three layers: a sensing layer, network layer, and application layer. The sensing layer consists of a wireless sensor network, based on Zigbee, a network standard that is specifically designed for low-power applications, as well as a GPS module. It is claimed that the system has good characteristics, such as „low power […], low cost, reliable data transmission, short delay, [and] large network capacity“ (Luo et al., 2016). On the network layer, the collected data is transmitted over mobile telecommunication networks. 2G, 3G and 4G networks are supported. Network management systems, i.a. for encoding and authentication purposes, are also part of the network layer. The application layer consists of several servers and the applications running on these servers, in order to provide a convenient interface for real-time monitoring.

The wireless sensor network communicates at a 2.4 GHz band, as it is specified in the Zigbee standard and allows transmitting data between 10 and 75 meters, depending on environmental characteristics, at a rate of 10 to 250 kbit/s. In order to maintain and manage the network easily, a star topolgy was chosen. The wireless sensors are integrated into the truck and power is supplied by the battery of the vehicle. These sensor nodes consist of three microchips that have to function reliably in cryogenic conditions: a temperature and humidity sensor integrated into a single chip, a microprocessor, and a radio transmitter that supports the Zigbee standard.

So-called sink nodes, mounted on top of trucks, are responsible for transmitting the collected data to servers via mobile telecommunication networks. The sink node contains the Zigbee router and a mobile network module. Besides 3G and 4G support, 2G is supported mainly because of the lack of coverage of newer generation networks in developing countries and remote areas. However, it is still sufficient as it can provide reliable data transmission at 20 to 40 kbit/s. Sink nodes also contain an alarm module that sends out information about improper temperature and/or humidity values. A GPS node, that works independently from the sink node, transmits geographic location data to the servers via mobile networks as well. Figure 10 shows the structure of the sensing layer.

On the application layer, servers in remote data centers receive data from the sink and GPS nodes, process this data and store it in databases. A monitoring software allows staff in offices to monitor temperature, humidity and location of the transported goods. Servers can send out alerts to employees on-site when values are not within an appropriate range. Historic data will be stored, so that it can be analyzed later on. This allows the identification of reasons if goods are damaged in the supply chain.

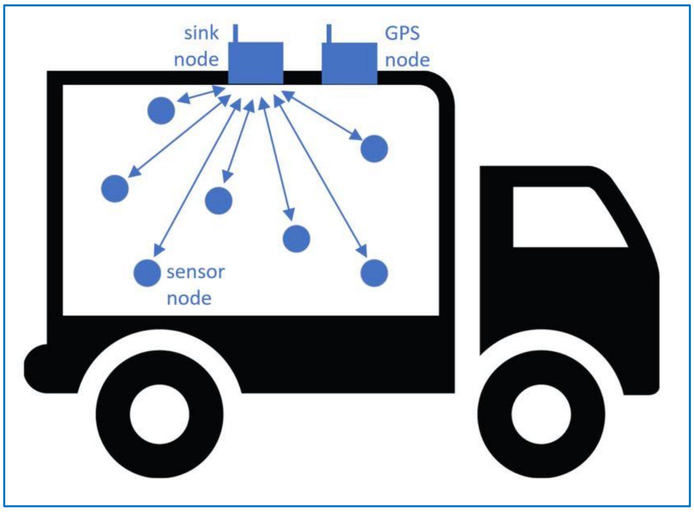

Figure 10 - Intelligent tracking system, sensing layer

3.3.5 Maersk: Remote Container Management

Maersk Line has implemented a system for monitoring its containers, called Remote Container Management (RCM). Containers are equipped with several sensors, such as temperature, humidity and CO_2 sensors, a GPS module, a modem, and a mobile network module. Thus, it can collect the atmospheric conditions and location of the stored cargo and share it wirelessly. The cargo ship has a satellite transmitter that receives the data from each container and sends it in real-time over the internet.

An online platform allows monitoring the containers and notifications can be sent directly to the customers if values of the measured quantities deviate from the limits. This reduces manual inspection of containers and thereby cuts operational costs to a great extent. Furthermore, malfunctions of containers and other incidents are reported immediately to relevant stakeholders, such as the RCM team on shore, staff on the ship, as well as equipment repair vendors.

With this insight, steps can be taken if the temperature control malfunctions or the conditions inside the container change for other reasons because the data is available in real-time. This requires of course the necessary staff on the shipping vessel in order to do repairs right away.

Figure 11 below shows how the system works. The use of satellite communication makes it possible to have real-time monitoring even in the middle of the ocean and it connects the vessels' data with offices, the shipping terminals at the ports and equipment management repair vendors that can provide replacement parts in case of broken equipment on the ship.

Furthermore, the system includes other than container data, such as a vessel's fuel consumption in order to optimize the operation of the entire fleet (Churchill, 2016).

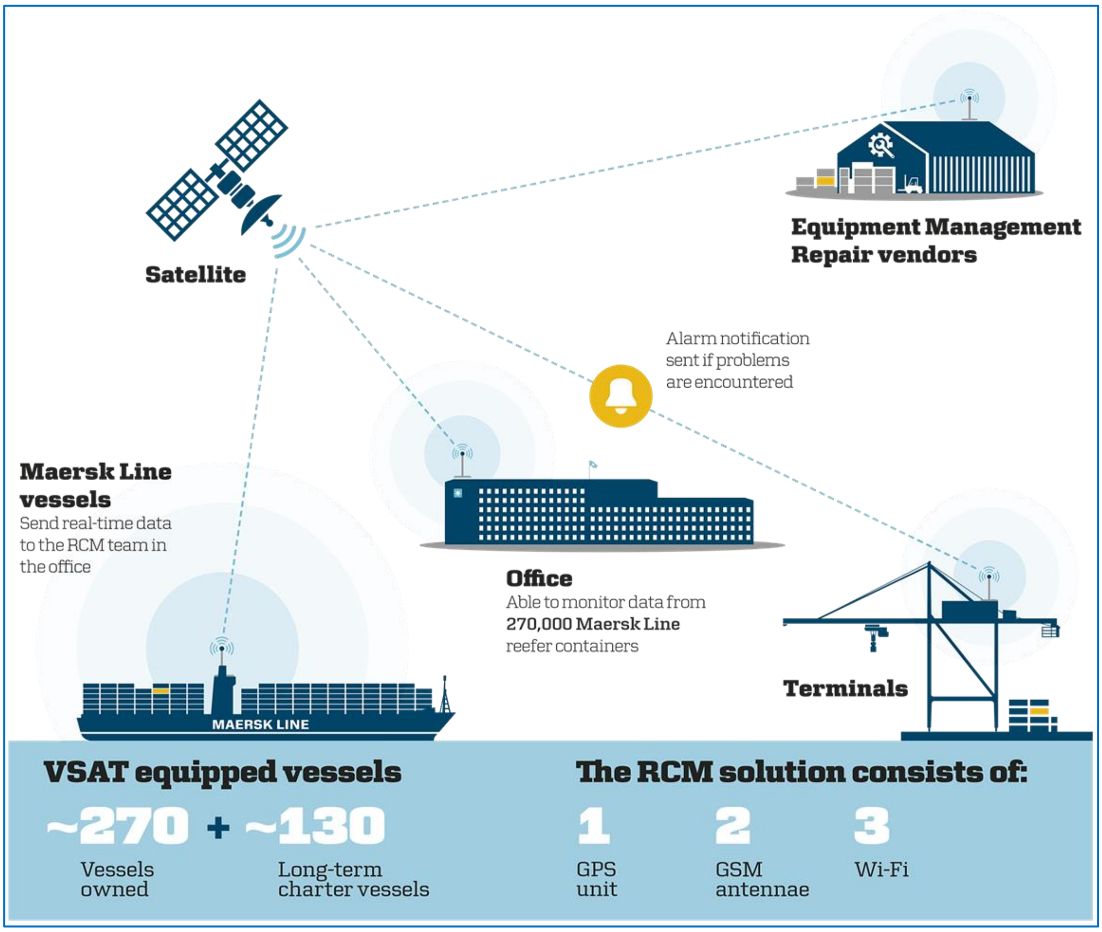

Figure 11 - Maersk Remote Container Management (RCM) overview (Churchill, 2016)

3.3.6 MOST Transport Monitoring system

MOST is a low-cost monitoring system for the transportation industry, sold by the Swedish company *Mobsentech*. It is device that comprises four different sensors, a GSM module, and a battery that lasts up to 100 days. It can be attached to the inside of a container and thus monitor several parameters: temperature, humidity, light intensity, and shock. The GSM module allows real-time monitoring and provides a cellular-based location tracking of the container. The sensors measure once per hour and the data is sent to a web-based platform where it can be monitored. The system also allows alerts via SMS and email if parameter limits are exceeded. Two different options exist for customers to choose from. The one-way option for $55 allows one trip to be monitored but the device cannot be used afterwards anymore. The subscription option is offered on a pay-per-month basis and allows the devices to be recharged and reused. It starts from under $22 per device per month (at 100 units, annual subscription), up to $30 per device per month (at 10 units, quarterly subscription) (Miovic, 2018).

3.4 Requirements Engineering

Requirements engineering is a process for managing the requirements of a system, which includes the elicitation and clear definition of requirements, as well as the documentation and maintenance of those. A requirement is defined by IEEE as

> *„a statement that identifies a product or process operational, functional, or design characteristic or constraint, which is unambiguous, testable or measurable, and necessary for product and process acceptability (by consumers or internal quality assurance guidelines)"* (Dick, Hull, & Jackson, 2017).

In other words, a requirement defines a certain characteristic of a product about what it should be able to do or how it is supposed to perform (Rogers, Sharp, & Preece, 2011). Requirements are the basis of a product and establish a common understanding of the problem that needs to be solved by the product. There is a variety of different types of requirements and it is important that these are defined clearly. Therefore, several methods exist in order to define and document these requirements.

3.4.1 Types of requirements

Requirements are often divided into *functional* and *non-functional* requirements. Functional requirements define what functions a system should have. For a logistics monitoring system, this could be the remote monitoring of temperature, humidity and location on a container level or the alerting in case of improper parameter values. Non-functional requirements, on the other hand, define criteria of how the system should operate or can also be seen as qualitative requirements. Examples are real-time connectivity throughout the entire transportation process or the cost of the system (Rogers et al., 2011).

Other requirements are *data requirements* that define aspects like the type, accuracy, up-to-dateness, etc. of the data the system is handling, such as data the system is displaying should not be older than one minute. *Environmental requirements* define the circumstances the system will run. This covers the physical environment (e.g. humid, dusty, remote place), social environment (e.g. sharing of data between different stakeholders across long distances), organizational environment (e.g. hierarchical structure of the involved organizations), technical environment (e.g. necessary technologies). *User characteristics* define the important attributes of different user groups, such as the educational background and nationality of the user group suggests the implementation of different language options or step-by-step instructions. Finally, *usability and user experience requirements* define aspects like the learnability (how easy it is to learn and understand the system) and the usefulness (how helpful is the system) (Rogers et al., 2011)

Summing up, there are various kinds of requirements, including but not limited to

- Functional requirements,
- Non-functional requirements,
- Data requirements,
- Environmental requirements,
- User characteristics,
- Usability and user experience requirements.

3.4.2 Data acquisition

In order to define different requirements for a system, data needs to be gathered. As with all kind of research, this can be done by collecting primary or secondary data. Primary data for establishing requirements are mainly collected through interviews, questionnaires or observation. Secondary data can be acquired by studying documentations or researching similar products (Rogers et al., 2011).

Rogers et al. (2011) specifies guidelines for the data collection in terms of requirements engineering. It is important to focus on the needs of the stakeholders, which can be done by observing the existing behavior or looking at support tools the stakeholders are using. Studying similar, existing products is also a good way to find out the stakeholders‘ needs. Furthermore, it is important to involve multiple representatives for each stakeholder group in order to have a more objective perspective. Moreover, establishing requirements is an iterative process. Therefore, it is a good idea to create task descriptions (e.g. use cases, scenarios) and (conceptual) prototypes in order to support the data collection process and establish a common understanding of the system.

3.4.3 Data analysis

The gathered data is mainly of qualitative, rather than quantitative, nature. There are different methods for analyzing qualitative data. One method is to *identify recurring patterns*, e.g. when multiple interviewees mention that real-time monitoring is of importance, then this is a recurring pattern that should be paid attention to. *Categorizing data* is another method, which is similar in a way. However, data is put into different categories, which allows to quantify the data, e.g. by counting how many problems there are of a certain category. One analysis method mainly used to examine existing products is a *hierarchical task analysis* (HTA). It begins with identifying the user goal or need, e.g. monitoring various parameters of goods during transport. This goal is then broken down into subtasks and sub-subtasks if necessary. A plan is then specified, which is a step-by-step scheme of the tasks that are performed. This helps to understand the interactions with the system at different abstraction levels. However, HTA is not suitable for complex tasks as it becomes very confusing (Rogers et al., 2011).

3.4.4 Requirements engineering framework

The requirements engineering process is an iterative process that helps to turn the stakeholder's needs into specific (sub)system requirements. Dick et al. (2017) proposed a framework for this process. The different levels of requirements can be seen in Figure 12. The number of levels depend on the complexity of the system. If the requirements are too abstract, it may be necessary to split further down into requirements of lower level components of the system.

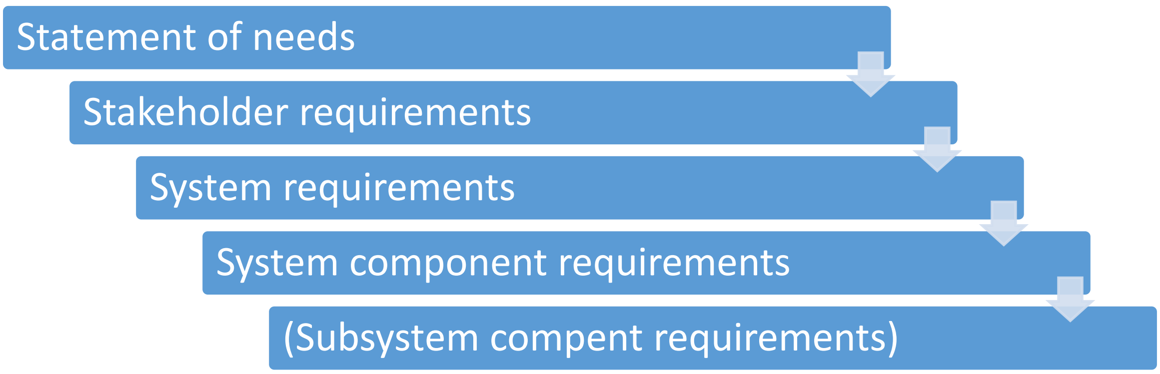

Figure 12 - Different levels of requirements

In order to define lower level requirements, a process has to be defined that takes the higher-level requirements as input. This process is illustrated in Figure 13 and has to be repeated until the necessary specificity of requirements is reached. The process has four steps:

- Agreement of input requirements
- Analyzing and modelling
- Deriving requirements
- Agreement of derived requirements

Assessing the input requirements involves aspects such as the completeness, clarity, and implementability of each requirement. For instance, if a requirement is ambiguous, this leads to rejection of this requirement and it has to be revised.

Analyzing the requirements is done with different methods, such as those explained in chapter 3.4.3. The use of models depends on the abstraction level. For stakeholder requirements, the most used models are use cases or user scenarios. Other methods include class, sequence, entity-relationship diagrams, or others.

Deriving the requirements is determining the lower level requirements through the analysis and modelling step, e.g. deriving requirements for components on the basis of the system architecture. It is possible that some of the derived and input requirements are identical.

Afterwards, the derived requirements have to be assessed as well. Here, it is mainly important that all input requirements are satisfied by one or multiple derived requirements and that each derived requirement satisfies at least one input requirement, directly or indirectly, meaning it is a necessary requirement. If an input requirement is not satisfied, the process is not complete. If a derived requirement is not necessary, it can be removed if the process before has been completed thoroughly (Dick et al., 2017).

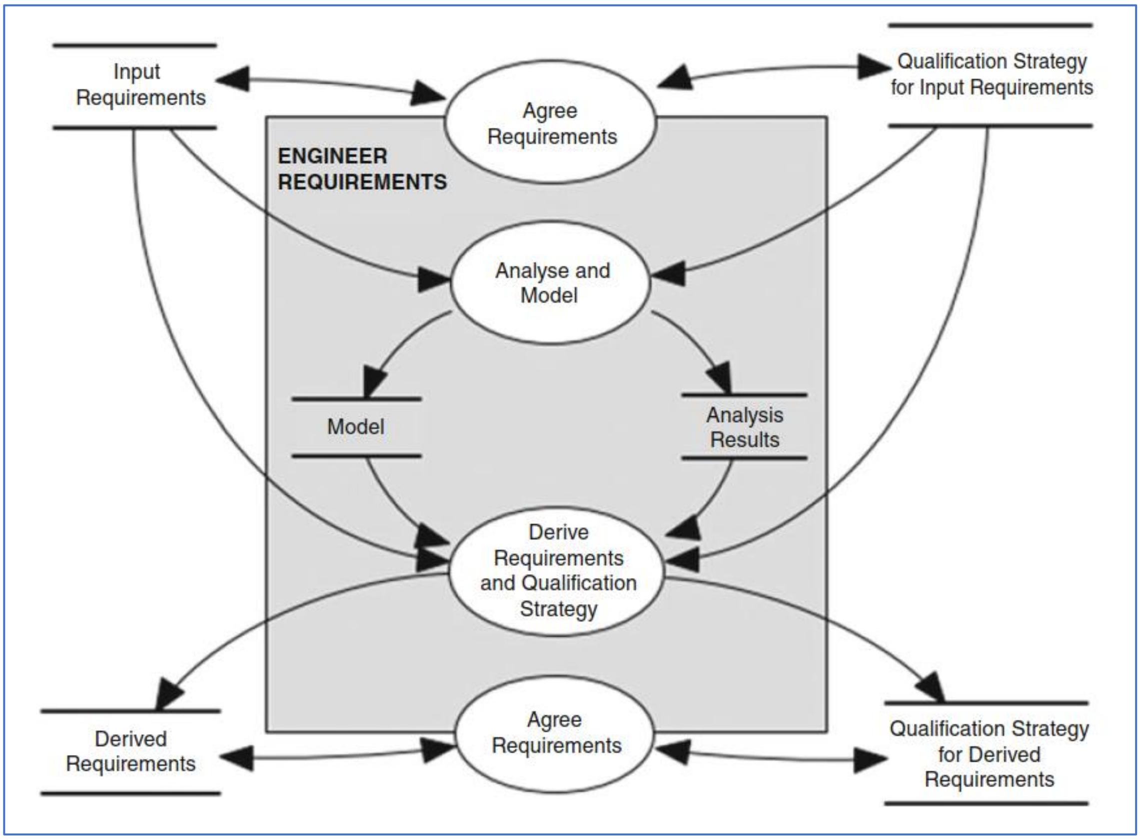

Figure 13 - Engineer requirements process (Dick et al., 2017)

3.5 Cost-benefit analysis

In order to make a decision for a product, service, project, etc., a cost-benefit analysis (CBA) is a common approach. In a CBA, all positive and negative impacts that the decision has, the costs and benefits, are listed and valued monetarily. Then, the net benefits are determined, which are the costs deducted from the benefits. Hereby, it is important to include the costs and benefits of all stakeholders. In practice, it is often difficult to assign a value to all the impacts (Boardman, Greenberg, Vining, & Weimer, 2006).

Two main types of CBA exist: *ex ante* and *ex post* analysis. An ex ante analysis is conducted before a project is started, while an ex post analysis is done at the end of it. The purpose of an ex ante CBA is commonly for deciding whether a project should be carried out, while the purpose of the latter is to learn which type of projects are worth to pursue in the future (Boardman et al., 2006).

Boardman et al. (2006) set out the following main steps in a cost-benefit analysis:

1. **Specify alternative projects.**

In theory, there can be a lot of different alternatives. A project has many different factors that determine the project. Changing just one of these factors can give multiple alternatives. A monitoring system for instance can have a certain number of sensor nodes per container, real-time connectivity or not, it can use different technologies in terms of communication and sensors, etc. Varying only one of these factors generates an alternative. Varying multiple factors results in a lot of different possible alternatives. In practice, in a CBA usually just two to five alternatives are analyzed (Boardman et al., 2006).

2. **Determine the stakeholders whose costs and benefits should be taken into account.**

In the second step, it must be decided, whose costs and benefits are included in the CBA. The analysis can be conducted from a broader perspective, also including those that are not directly affected by the project. It can also be conducted from a narrower perspective that only includes effects on directly affected stakeholders.

3. **List the costs and benefits and select indicators for measuring the impact.**

In this step, the impacts (costs and benefits) are listed. Only impacts that affect any of the stakeholders in some way are included in the cost-benefit analysis. Boardman et al. (2006) state that there has to be a "cause-and effect relationship between some physical outcome of the project and the utility of human beings with standing [stakeholders]". The indicators for measuring the impact are needed to quantify the impact. This can be for example time savings, or specific monetary costs.

4. **Quantify costs and benefits over the project life time according to the measurement indicators.**

Quantifying the costs and benefits means to assign a value to each listed impact, based on measurement indicators. These values are generally estimates that are based on research. However, estimating is often difficult because it is not easy to predict how the stakeholders will react to the changes that the project brings about. Furthermore, the project can affect other stakeholders that have not been taken into account, in a way that changes costs or benefits of the analysis. For example, a third party company could develop a complementary service that solves a problem of monitoring systems, thus making it more beneficial. Additionally, the prediction of certain values could require some specific scientific knowledge that is simply not available or not certain.

5. **Assign a monetary value to the costs and benefits.**

The next step is to monetize the values of the previous steps, i.e. assigning a value in dollars (or another currency) to it. These values should also be based on research, but it can still be difficult, e.g. if a project helps to save lives, it is difficult to estimate the monetary value of a saved life.

6. **Calculate present value of future costs and benefits.**

Calculating the present value of future costs and benefits means to discount the value with a certain discount rate *s*, named the social discount rate. The present value of the impact *I* in year *t* can be calculated by using the following formula, where *n* is the project life in years:

$$PV = \sum_{t=0}^{n} \frac{I_t}{(1+s)^t}$$

This formula can be used to calculate the present values of both costs and benefits, which correspond to the impact.

7. **Calculate the net present value of each alternative.**

The net present value of one alternative is simply subtracting all net present values of the costs from all net present values of the benefits:

$$NPV = PV(B) - PV(C)$$

8. **Perform a sensitivity analysis.**

Generally, a sensitivity analysis should be performed at the end of the CBA to handle uncertainties that surely arise in the previous steps. A sensitivity analysis is supposed to show how the net benefits of the alternatives can change with different, but reasonable assumptions. The more the net benefits vary, the less convincing the results of the cost-benefit analysis are. Generally, a complete sensitivity analysis is not feasible because there can be millions of different assumptions. Therefore, a general approach is a partial sensitivity analysis, where single assumptions are varied while others are kept constant. Another approach is a worst- and best-case analysis, where, as the name suggests, worst and best cases are analyzed.

9. Recommend one of the alternatives.

The final step is to give a recommendation based on the net present value of the alternatives. This is usually the one with the highest net benefits.

4 Findings

4.1 Findings from interviews

The interviews were conducted with representatives of logistics companies that have insights and knowledge about logistics monitoring systems. It gives an understanding of different real-life cases of deployed monitoring systems and what current challenges are. It is important to note that the interviews represent subjective views and statements should not be taken as a fact. By conducting these interviews, it became clear that there is no standard for monitoring systems and different companies in the industry are not on the same level in terms of the deployed technology, which is most likely due to the various differences in goods being transported and what the companies are specialized in.

The conducted interviews are numbered, so each piece of information can be referred back to a specific interview:

1) Interview with Kuehne+Nagel A/S
2) Interview with Scan Global Logistics A/S
3) Interview with Freja Transport & Logistics A/S

Numbers in brackets indicate, which interview the piece of information can be referred back to. If no number is specified, the information comes from all interviews.

Monitoring systems are used by all of the interviewed companies, and they use their own system, however, one of the companies' system is only for monitoring the location via GPS (2). Regardless of the use of own equipment, two companies reported to use monitoring services offered by the carrier (2,3), such as the Maersk system (see chapter 3.3.5). All systems are monitoring on a container level, rather than a pallet or item level. While the equipment of one company is simply disposed after transportation because of the cheap costs (1) (which is the MOST system, see chapter 3.3.6), the other two companies reuse the monitoring equipment (2,3). Only one company's equipment is integrated into the container (3). Two companies report that the monitoring devices are battery-powered (1,3). While the systems being used by the interviewed companies are all supposed to support real-time connectivity, two companies report connectivity issues (1,2), so real-time monitoring is only possible with restrictions. The benefits of monitoring systems are mainly for documenting reasons (1,2), in order to have proof for liability issues (1), if for instance the temperature is not kept within the agreed range. The other reason for the customer is to have documentation for legal responsibilities (2), such as proof that the cold chain has not been broken. Otherwise, it is to increase the transparency of the transportation process and increase trust between the customer and carrier (3).

Regarding the parameters being monitored, temperature and the time the food is being transported are the most important factors that affect the quality of food (1). However, it is reported that food spoilage mainly occurs due to improper packing and loading of goods or due to insufficient conditions before the transportation process, rather than due to technical reasons, such as failure of temperature control (1). For pharmaceuticals, temperature and humidity are most important (3).

Regarding the transport of pharmaceuticals, there are strict regulations in place (1). However, these often just evolve around documenting the process and the maintaining of the cold chain (2). In air transportation for instance, it is not required to monitor and control temperatures, but simpler solutions are used, such as transporting pharmaceuticals in boxes filled with ice (2). Monitoring the temperatures in this process could make documenting it more efficient and less erroneous (2).

The main challenges mentioned in the interviews were as follows.

- The costs of monitoring systems are too high (2,3).[1]
- Real-time connectivity is often not available (1,2).
- The material flow of the equipment (logistics of the equipment) has to be ensured (2), meaning the equipment needs to be where it is needed.
- The system should be easily scalable, extendable and standardized (3).
- The system should help to document processes for regulatory matters (2).
- Real-time monitoring is only beneficial if the issue can be resolved directly (2).

Another issue discovered is that in some cases two monitoring systems are used, one by the carrier and one by the freight forwarder (1). This is the case because some carriers have monitoring

[1] The interviewed companies were not willing or able to share specific costs. Company (2) mentioned an annual license fee of $1000 per user, excl. Implementation and operation costs (see Appendix B).

systems deployed but don't share the data with the consignee, which requires a separate system if monitoring is necessary, which is managed by the freight forwarder (1).

4.2 Findings from literature

The literature review is based on the search protocol in Appendix A. The goal was to find scientific literature about proposals and implementations of monitoring system to analyze commonalities. 30 references were found, from which 20 were identified as relevant. The following list shows the titles of the relevant papers. A full list of the search results, including all 30 references, can be found in Appendix A. The references here are numbered, so that it can be referred back to a specific reference in the text by indicating the number in brackets.

1) A low-power wireless UHF, LF sensor network with web-based remote supervision (Heidmann et al., 2013)
2) A novel deployment of smart cold chain system using 2G-RFID-Sys (Y.-Y. Chen et al., 2014)
3) Analysis of the Future Internet of Things Capabilities for Continuous Temperature Monitoring of Blood Bags in Terrestrial Logistic Systems (Castro, Jara, & Skarmeta, 2011)
4) Cost-benefit model for smart items in the supply chain (Decker et al., n.d.)
5) Design and simulation of self-powered radio frequency identification tags for mobile temperature monitoring (Chu et al., 2013)
6) Developing an Ontology-Based Cold Chain Logistics Monitoring and Decision System (Wang, Yi, Zhu, Luo, & Ji, 2015)
7) Development of wireless sensor module and network for temperature monitoring in cold chain logistics (C.-M. Li et al., 2012)
8) The Phase Space as a New Representation of the Dynamical Behaviour of Temperature and Enthalpy in a Reefer monitored with a Multidistributed Sensors Network (Jiménez-Ariza et al., 2014)
9) Dynamic and Heterogeneous Wireless Sensor Networks for Virtual Instrumentation Services: Application to Perishable Goods Surveillance (Seco, Bermudez, Paniagua, & Castellanos, 2011)
10) Improvement in the tracking of special loads by using a three-level RFID system (G.-Escribano, de Dios, Pastor, & García, 2012)
11) Mobile wireless sensor system for tracking and environmental supervision (Sarmiento M et al., 2010)
12) Performance of ZigBee-Based wireless sensor nodes for real-time monitoring of fruit logistics (Ruiz-Garcia, Barreiro, & Robla, 2008)
13) Predictive Analytics based on CEP for Logistic of Sensitive Goods (Nechifor, Petrescu, Damian, Puiu, & Tarnauca, 2014)
14) Reducing food losses by intelligent food logistics (Jedermann, Nicometo, et al., 2014)

15) Research on Application of WSN in Cold Chain Logistics‘ Warehousing and Transportation (H. Zhang & Yang, 2017)
16) Smart Sensor Identifier (S2I) Application and Tracking of Sensitive Products (de la Fuente Ruz, Higuera, Duro, Álvarez, & Sánchez, 2007)
17) SMS-CQ: A quality and safety traceability system for aquatic products in cold-chain integrated WSN and QR code (Xiao, Fu, Zhang, Peng, & Zhang, 2017)
18) Telematic platform for integral management of agricultural/perishable goods in terrestrial logistics (Santa, Zamora-Izquierdo, Jara, & Gómez-Skarmeta, 2012)
19) Using Dynamic WSNs in Smart Logistics for Fruits and Pharmacy (Bijwaard et al., 2011)
20) Wireless Sensor Networks for Logistics and Retail (Z. Zhang et al., 2009)

19 out of the 20 articles have an engineering perspective, while one of the articles include a cost-benefit model for logistics monitoring systems (1). While all of the papers are about a monitoring system for the transportation of goods, some of the papers additionally include monitoring during warehousing of goods or even keeping track of the goods in retail.

The articles focus on different aspects of logistics monitoring systems, giving insights into different issues regarding the implementation and practical use of such systems. The following table shows different categories of focus areas that the articles are examining as well as the number of articles per category.

Table 1 - Literature review: categorization of focus areas

Category	Number of articles	Articles
Data models / Shelf life models	4	6, 13, 14, 19
Power supply and power consumption	3	1, 5, 12
Reliability of communication (connectivity)	3	7, 12, 18
Low-cost implementation	2	2, 16
Reliability of data/measurements	2	1, 12
Flexibility/Scalability of system architecture	2	9, 19
Temperature variations inside the container	1	8
Examination of opportunities and challenges	1	3
Examination of costs and benefits	1	4
Examination of requirements	1	17

The articles that do not appear in the table are describing the implementation of their proposed system architecture. In 12 papers, the research is backed up by experiments and tests (1, 6, 7, 8, 10, 11, 12, 14, 17, 18, 19, 20), of which 11 projects were real experiments, rather than simulations (1, 6, 8, 10, 11, 12, 14, 17, 18, 19, 20).

Almost all the papers that describe a complete system have in common that they are using a 3-layered system approach, consisting of application layer, network layer and sensor layer (1, 2, 6, 7, 9, 11, 14, 15, 16, 17, 18, 19, 20) as depicted in Figure 14. The application layer contains a remote server that receives monitoring data through a gateway, generally through mobile network communication. The gateway is part of the wireless sensor network and can therefore communicate with the sensor nodes. The wireless sensor network works on two layers, the sensor layer and the network layer.

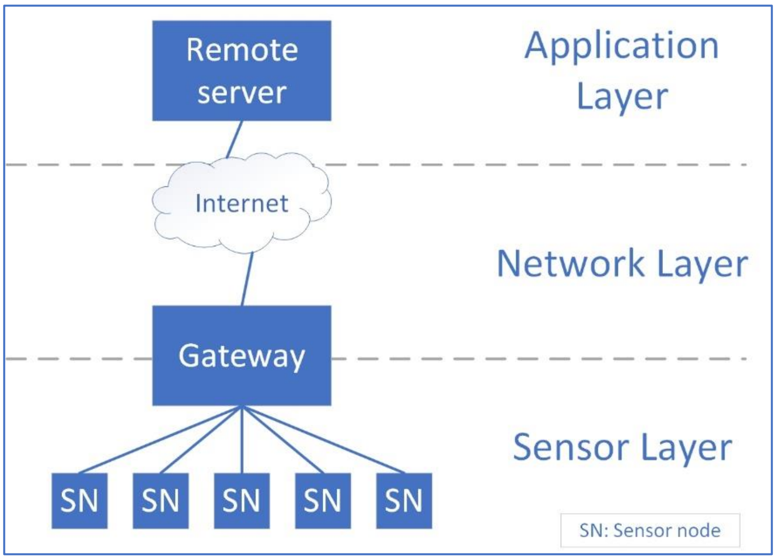

Figure 14 - General system structure of logistics monitoring systems

The wireless sensor networks are based on different technologies, whereas RFID and the IEEE 802.15.4 standard is used exclusively in the monitoring systems described in the articles. While only one of the systems uses 6LoWPAN (3), a network technology based on IEEE 802.15.4, seven systems use ZigBee (6 ,7, 10, 12, 15, 17, 18), which is also based on IEEE 802.15.4. The *Intelligent Container*, described in chapter 3.3.1, is also based on 6LoWPAN. In two papers, it is specified that IEEE 802.15.4 is used, however not which overlying technology (9, 19). Ten systems on the other hand make use of RFID technology (1, 2, 3, 5, 8, 10, 11, 16, 18, 20).

One system uses a 4-layered architecture. The wireless sensor network works on three layers, whereas first and second level communication is based on RFID and third level communication is based on ZigBee (10).

Reliability of wireless communication

The reliability of radio communication on the WSN level is important in order to enable real-time monitoring. Attenuation of the signal is a challenge, especially when the cargo has a high water content, as water is attenuating the signal more than air (7). This challenge is also examined in the *Intelligent Container* (see chapter 3.3.1), which is especially a problem for higher frequencies, e.g. in the license-free 2.4 GHz ISM band. However, not only the water content of goods, but also the space between pallets and container walls affects radio link quality (Jedermann, Pötsch, & Lloyd, 2014). In (7), a sufficient link quality of 95% could be achieved by deploying a star topology and keeping 8 cm between vertical layers of water-filled styrofoam boxes, keeping in mind that the transceiver is mounted on the outside of the box. Whereas in the *Intelligent Container*, a maximum range of 0.5 m could be achieved with 1 mW transmission power at 2.4 GHz, requiring a mesh topology with a high density of sensors inside the container (Jedermann, Pötsch, et al., 2014). Distinct lower signal attenuation at 1 GHz and lower makes other communication technologies more attractive, according to Jedermann et al. (2014), e.g. the 433 MHz ISM band.

The results in (12) also report that attenuation is highest when sensors are placed inside the boxes, but there were generally no problems in the communication with the common ZigBee module *Xbee-PRO*, however using as much as 60 mW transmission power.

(18) uses passive UHF RFID tags (865-960 MHz) only to track goods. The reading range of these tags was tested, and the results showed a maximum range of 10 m by deploying multiple antennas around the door of the truck trailer. However, there were no tests of goods with high-water content reported.

Power supply / Power consumption

In (1), a low-power monitoring system based on active RFID is proposed. It proposes the use of LF radio signals to wake up the sensor nodes when data should be transmitted via UHF RFID. With this combination, a sleep mode power consumption of 10 µW could be achieved, as well as 122 mW during data acquisition and transmission at 10 mW transmission power (assuming 3.3 V power supply). This results in about 520 µW in total for measurements and transmissions every 60 seconds. A similar approach was taken in (16), except that a 2.4 GHz communication is used.

An alternative is to avoid the use of batteries in general. Self-powered semi-passive UHF RFID tags, which usually require batteries, are proposed in (5). The idea is to use a piezoelectric power supply (PPS). In tests, 283 µW could be harvested by vibrations with a frequency of 1 Hz and a force of 650 N. This force corresponds to the gravitational force on earth affecting an approx. 66 kg heavy object. Therefore, the required force and frequency could be achieved by a truck's vibrations affecting heavy load. The RFID tags use the IDS-SL900A chip, which integrates an RTC and temperature sensor with a maximum power consumption of 225 µW. This is lower than the harvested energy by the PPS, which would make the self-powered tags work properly in theory. However, in practice, the harvested energy by the PPS is often lower than the maximum. If the tags are programmed to log data in time intervals, the tag could be an alternative for the transport of heavy items. However, in (7) the results are only generated in a simulation and should be tested in a real scenario. The transmission range of these tags is not assessed in the article.

Article (12) examined the battery life of ZigBee sensor nodes in different temperature conditions. The experiments showed clearly that lower temperatures drain batteries much quicker. The battery life of the devices powered by two AA batteries were less than 50% at 0 °C compared to 20 °C.

Data reliability

Article (1) describes the use of a 3D-LF antenna to measure the signal strength on three axes for the purpose of estimating the position of the sensor nodes inside the container. Problematic was the discharge of the battery voltage because it affected the measured signal strength due to a change in the reference voltage. This can also be an issue for other sensors that require a stable reference voltage, as described in (12). It is reported that the reliability of the temperature and humidity measurements were affected by the battery voltage. When the voltage reached a certain threshold, the measurements were incorrect. Moreover, the position of the temperature sensor on the device can affect the accuracy of measurements. When the sensor is placed close to a module with high power consumption, such as a GPS module or communication module, the heat dissipation of the module can affect temperature measurements (12).

Temperature variations in container

In (8), temperature and humidity variations were measured by installing 60 temperature and humidity sensor in a container. The experiment was conducted in a real transport scenario, shipping lemons from Uruguay to Spain by means of two different shipping vessels and truck. The sensors were distributed equally along the load and attached inside the transportation boxes. Results showed that the average temperature measured by all sensors was 2.7 °C higher than the set point of the temperature control, compared to ±0.5 °C temperature variations recommended by European standards for food distribution (8). Furthermore, the highest measured temperatures were as high as 6.5 °C above the set point, measured at the evaporator inlet. The sensors in the upper part of the container measured the highest temperature variations, as well as the highest temperature. Fruits in the upper part were in fact in risk of rotting. Regarding relative humidity, variations of 25 percentage points (70% vs. 95%) were recorded, highest close to the cold unit and lowest at the door. In article (19), it is mentioned that temperature differences inside a container can be up to 12 K.

Cost and benefits

Article (2) proposes a low-cost system on the basis of passive RFID tags, described in chapter 3.3.3. It uses monitoring of environmental parameters, such as temperature and humidity, on container-level and tracking of goods on item-level. The downside of this is that temperature fluctuations inside the container are not captured. The upside is the costs of the system as passive RFID tags are fairly cheap: they can cost as low as $0.10 (Advanced Mobile Group, 2016).

In (16), a system based on 2.4 GHz communication is proposed, using low-cost components. A sensor node was developed for about 12€ (ca. $14.4), as well as a base station (gateway) for 86€ (ca. $102.7).

MOST is a monitoring system developed by the Swedish company *Mobsentech* (see chapter 3.3.6). It offers two different options to choose from: a one-way option, where the device can only be used for one trip, for a price of $55, as well as a subscription model from ca. $22 per month and device (at 100 devices and annual subscription) (Miovic, 2018).

However, it is not only equipment costs that need to be taken into account. Operational and maintenance costs can also make a large share of the total cost. One part is costs for mobile data communication in order to send data to a remote server. For oversea shipping, there is however problems with connectivity. Therefore, satellite communication can be used, e.g. in the Maersk system (see chapter 3.3.5) and in the *Intelligent Container* project. In the *Intelligent Container*, the Iridium satellite network is utilized. The costs are at $1.15 per kB of data.

Article (4) proposes a cost-and-benefit model for tracking and monitoring systems from the perspectives of supplier, shipping company and consignee. It identifies the costs and benefits for the three stakeholders as can be seen in Table 2 below.

The proposed quantification model describes the costs and benefits in a simplified and ideal transportation scenario, such as the error-free functionality of the monitoring system, the shipment of a single type of good and the assumption that all parameters can be quantified. It is also pointed out that monitoring systems often function not totally error-free, mainly due to unreliable communication and the power supply of sensors. The latter has a significant impact on the operational costs (4).

Table 2 - Costs and benefits based on article (4)

	Supplier	Shipping company	Consignee
Costs	• Higher shipping cost due to monitoring system	• Implementation and operation cost of monitoring system • Penalty for defective/ • perished goods	• Higher shipping cost due to monitoring system
Benefits	• Higher turnover because higher sales of products with sufficient quality • Clear assignment of responsibility if goods quality is insufficient • Lower processing cost of returned goods (defective/perished)	• Advantage over competitor due to higher shipping throughput • Enables potential for optimization of shipping process • Higher transparency → higher customer satisfaction	• Reduced amount of defective/wasted goods • Knowledge about the amount of wasted goods prior to delivery

Opportunities and challenges

Article (3) analyses opportunities and challenges of item-level monitoring systems in particular. The discussed opportunities and challenges are as follows.

Table 3 - Opportunities and challenges based on article (3)

Opportunities	Challenges
• Automatically adjust temperature based on the requirements of the transported goods • Alarm-based in instead of continuous monitoring → reduces network traffic • Higher trust level because verification can be done on item level	• Managing all gathered information in a centralized manner • Sending a large amount of data at one time from hundreds of sensors

Furthermore, challenges in regard to food losses are described in article (14). Spoilage arises due to many different factors that can be split into two main factors: overproduction and natural decay. While overproduction cannot be addressed by more efficient transportation, the second factor can be. Reasons for natural decay are that farmers do not directly pre-cool products, transportation temperature conditions are not optimal and that customers do not store products at appropriate temperatures. There are several reasons for improper temperature conditions during transportation, some of these are:

- Airflow in containers is often blocked, e.g. due to wrong pallet positioning.
- Reefer containers require two weeks to reach the set temperature point.
- In air transportation, there are high temperature variations during flight operations.

User and system requirements

Article (17) describes a system for monitoring the cold chain processes of fish and seafood. Before developing the system, detailed research and analysis has been conducted, consisting of field observation, as well as surveys and interviews of managers and cold-chain workers in order to elicit requirements for the monitoring system. Ten requirements are described in the paper, consisting of functional and non-functional requirements (cf. chapter 3.4.1). The most relevant ones are listed here:

- Real-time monitoring of temperature during cold chain logistics processes for managers
- Generation of reports about the entire cold chain process for management reference
- Show temperature information to cold-chain workers on the spot
- Warning signal when temperature thresholds are exceeded

- Define responsibility when product quality or safety is compromised
- Easy-to-use system and easy to retrieve historic information
- Easy to deploy system on the spot

Furthermore, article (16) defines four main parameters to take into account when developing a logistics monitoring system: cost, operational freedom, size, special features. However, it is not clear what operational freedom and special features exactly mean. Other important parameters are reliability, solidity, and user-friendliness.

In article (3), requirements for monitoring blood bags during transportation are listed, such as easy checking to evaluate the blood bags' condition at any time; variety of alerts (temperature out of range, delivery delay, etc.); temperature-time graphs for easy understanding of when and where the problem occurred.

On the level of system requirements, article (19) defines several requirements for the wireless network infrastructure. It should be reliable, meaning 99% of message should arrive, whereas the latency can be high, as a few seconds delay is generally no problem for logistics processes. The system should be easily scalable, so that it is no problem to add more sensor nodes. Moreover, it should allow multiple networks to coexist, e.g. a truck can consist a network by itself, but in a distribution center where there are multiple trucks, the different networks should be able to combine.

Other information

As reported in the interviews, besides the temperature, the transport time affects the quality of food as well. Article (8) describes an experiment in a real scenario with a transportation time of 31.7 days, from Montevideo in Uruguay to Murcia in Spain. The results showed that 39.7% of the time, which corresponds to more than 12.5 days, were delay times, such as loading procedures, inspection or simply waiting time. While this issue does not have directly to do with monitoring systems, it can be investigated with the help of monitoring the geographical location. If, for instance, a ship does not move for longer than expected, this can be observed with a monitoring system. The carrier has then the opportunity to intervene.

Furthermore, several articles discussed the use of data models or shelf life models to predict the quality of products based on the measured environmental quantities because the remaining shelf life depends to a large extent on the temperature profile, but also on humidity and ethylene concentration, according to article (19). Referring to chapter 3.2, this belongs to the *analyzing* step in the information value loop. As this is not directly related to the objectives of this project, it is not further discussed in this report.

5 Analysis

This chapter will show the results about the requirements of wireless sensor networks used for monitoring in logistics, as well as a cost-benefit analysis of monitoring systems.

5.1 Requirements of monitoring system

In this chapter, the insights on wireless sensor networks and monitoring systems from literature review and from the interviews with logistics companies are used to conduct a requirements analysis, so that requirements for a monitoring system solution can be specified. This process is performed according to chapter 2.2.

5.1.1 From Statement of needs to system requirements

The statements of needs are extracted from the interviews and literature review. The requirements based on the interviews are determined by examining, what the interviewees expressed as the most important problems and challenges. The requirements based on literature are determined by examining the different categories in chapter 4.2 and focusing on challenges that were reported in the used sources.

The following list shows the extracted requirements. Numbers in brackets indicate where this piece of information came from and allows easier traceability of the information. The same numbering system is used as in the Findings chapter (see chapter 4). The number is preceded by a letter that indicates whether the information is extracted from an interview or literature (L = literature, I = interview).

1. The costs of a monitoring system must be lower than of today (I2, I3).
2. Real-time monitoring is beneficial (I1, I2) if the issue can be resolved directly (I2).
3. The logistics of the monitoring system equipment has to be ensured (I2).
4. The system should be scalable, flexible and extendable, in terms of the type of sensors being used and the number of nodes in the network (I3).
5. The system should help to document processes for regulatory matters (I2).
6. The geographical location is an important parameter to monitor (I3).

7. Enough sensor nodes are required inside a container/trailer in order to measure temperature differences and physical shock (L).
8. Reliable communication technology and advantageous placement of sensor is required so that attenuations due to high load and high water content in cargo can be counteracted (L7, L12).
9. Low-power operation of sensor nodes is required so that the power supply is sufficient for long transportation processes.
10. Sensor measurements should fulfilll standards for goods transportation (L8).
11. Responsibility should be defined when product quality or safety is comprised (I1, L4, L17).

Statement 1

First, of all, these needs are assessed in terms of unambiguity and clarity. Statement (1) is not ambiguous but also not entirely clear. It is not clarified what cost it is based on and neither what an acceptable value for the costs would be. As mentioned in the interviews, it depends a lot on what the customer is willing to pay and how much the consignment is worth. Unfortunately, the interviewed companies were not willing or able to share specific costs. However, the fact that one of the companies reported very low cost of their system (I1) shows that there might be a lack of information among transportation companies about existing systems and prices may vary greatly. The cost issue is further explored in chapter 5.2.

Statement 2

Subsequently, statement (2) is unambiguous and clear. It states that the system should support real-time monitoring, meaning that the data on the remote server should be up-to-date at any time. A latency of several seconds is however allowed. In order to enable real-time monitoring, both the communication on the sensor layer, as well as on the network layer (see Figure 14 in chapter 4.2) have to work reliably throughout the entire transportation process. As the communication on the sensor layer is covered by statement (7), this statement mainly concerns the network layer communication. On sea transportation, there is mostly no mobile network coverage. Therefore, a satellite network is preferable here. This, however, is detrimental to a low-cost solution as satellite communication is much more expensive than regular mobile data communication (cf. chapter 4.2, cost and benefits). Therefore, it is preferable to have a flexible solution that allows the usage of a satellite network module for sea shipping and a regular mobile network module for land transportation or where real-time monitoring is not necessary. This is also in line with statement (4). But even if no real-time connectivity is available to the remote server, staff on the ship or other means of transportation can be alerted if the required conditions inside the container are not met. This requires a local communication link on the vehicle, from the container to the staff. A WLAN network would be a possible solution. This is further discussed in chapter 7.

Statement 3

Statement (3) says that the logistics of the monitoring equipment has to be ensured. That means, it has to be ensured that monitoring devices, once arrived at the destination, have to be brought back to the supplier or another departure location, where they can be deployed in order to not waste resources. One option is to integrate the devices into the container. However, then there is the same problem with the logistics of the container, which is even a problem today (see Appendix B, Interview with Scan Global Logistics). The problem with an integrated solution is also that sensors could only be placed in the walls, floor or ceiling of the container, which makes it however impossible to measure conditions inside pallets or transport boxes. Another option that could resolve the problem of equipment logistics is to make the cost of the system so low that devices can be disposed after one consignment. This, however increases the total cost because new equipment has to be deployed for each consignment, turning the cost of purchase into a cost per consignment. Furthermore, it would be detrimental to the sustainability of the overall system because a lot of electronic waste is produced. This challenge is further discussed in chapter 7.

Statement 4

Statement (4) stipulates that the system should be scalable, flexible, and extendable in terms of type of sensors being used and number of nodes in the network. It is not entirely clear what type of sensors can be necessary for monitoring, which greatly depends on the goods being shipped. However, looking at existing systems can bring more clarity here. Temperature variations are the most important factor that affects the shelf life of food products. However, humidity, physical shock, and CO_2, O_2 and ethylene concentration are also playing a role (Bijwaard et al., 2011; Jedermann, Nicometo, et al., 2014). Industrially used systems implement for example temperature, humidity, light intensity and shock sensors (see chapter 3.3.6). It is important that sensor nodes provide standardized interfaces so that a variety of sensors can be plugged into the node if needed. Modules with commonly used sensors should therefore be developed, using the same standardized interface that the sensor nodes provide. Regarding the number of sensors that should be supported in one network, it goes hand in hand with statement (7). The number of sensor nodes in the systems described in the articles of the literature review range between 10 and 105 per container (Heidmann et al., 2013; C.-M. Li et al., 2012), which will here be used as a reference point. This can be easily achieved by ZigBee or 6LoWPAN, which is preferable for other reasons, such as low power consumption, compared to other PAN technologies, such as Bluetooth.

Statement 5

Statement (5) lays down that a monitoring system should help to document processes in order to satisfy regulatory matters. It is not clear which regulations it concerns and what exactly has to be documented. This must be ascertained by further interviews and literature research. However, it will be most likely a documentation in the form of a report, satisfying the formal requirements of the regulations in question, e.g. by confirming that the cold chain has not been broken during the logistics process.

Statement 6

Statement (6) states that the monitoring system needs to keep track of the geographical location. A GPS module uses a lot of energy, which is counterintuitive to the low-power requirement. Furthermore, GPS often does not work inside, which requires the deployment of an antenna on the outside of the container. However, in a logistics scenario, the required accuracy of the location of goods usually does not need to be very precise, generally only several kilometers to track the area where the goods are (Z. Zhang et al., 2009). Therefore, the cell localization capability of the mobile network module can be used. However, this is not available if satellite network communication is used instead, e.g. on sea shipping. In this case, GPS can be used.

Statement 7

Statement (7) is a requirement regarding the deployment and depends on how the sensors are set up inside the container. Jiménez-Ariza et al. (2014) described a setup of 60 sensors, equally distributed in the container to measure temperature variations. Therefore, this number can be used as a reference point. However, it surely depends on the specific goods, to which extent the variations inside the container need to be captured. In Jiménez-Ariza et al.'s article, ten groups of sensors where identified because several sensor had very similar patterns of temperature variations and could be grouped together. Therefore, it may be sufficient to deploy ten sensors inside a container. As discussed under statement (4), it should be possible to choose a variable number of sensors.

Statement 8

Statement (8) concerns the reliability of communication inside a container, taking into account the load capacity, especially when the cargo has a high water content because of the attenuation of radio signals. The link quality between nodes also depends on the placement of the sensor nodes. When they are attached to the outside of boxes, the attenuation is not a big problem as C.-M. Li et al. (2012) reported. However, then the environmental conditions are measured outside the box as well, which is not as accurate. An option would be to place the sensor module inside the box, while the other components of the sensor nodes are located outside. Yet, this requires a complex installation of the nodes that increases the operational costs by far. This seems not be a feasible solution in an industry where time and cost are the main requirements. When the entire sensor nodes are placed inside boxes, it on the other hand decreases the link quality a lot (see chapter 4.2, Reliability of wireless communication). Jedermann et al. (2014) recommends the use of communication technologies on frequencies of 1 GHz and lower, such as the 433 MHz ISM band. The problem here is that this frequency band has no worldwide availability unlike the 2.4 GHz band, which would be a problem for intercontinental consignments. Ruiz-Garcia et al. (Ruiz-Garcia et al., 2008) showed that the use of higher transmission power of 60 mW (compared to 1 mW what Jedermann et al. tested) showed no problems in the link quality. However, the battery life of a sensor node with two AA batteries was limited to 4500 minutes at 0 °C, corresponding to only 3 days and 3 hours. Energy-saving algorithms were not implemented. It is necessary to find a compromise between availability of frequencies, power consumption, and sensor placement. Nascimento Nunes et al. (2014) showed that it is also possible to predict the shelf life of fresh fruit by only measuring surface temperature of boxes, rather than temperatures inside boxes. Therefore, it is proposed here that sensor nodes can be placed on the outside of boxes while having a higher transmission power (than what Jedermann et al. used) of 10 mW at 2.4 GHz to ensure that data can be transmitted reliably. However, this needs to be tested in a real setting. The 2.4 GHz is chosen because it is available worldwide.

Statement 9

Statement (9) says that a low power consumption is required so that the battery life of sensor nodes covers at least the duration of one consignment, which can be more than one month. Including a buffer time, a battery life of at least 40 days should be achieved. As the operational costs should be kept fairly low, the use of regular AA alkaline batteries is one option. Three batteries (3x 1.5 V) would be necessary to supply enough voltage for a sensor node running on 3.3 V, which is a very common supply voltage for communication and sensor modules. More batteries would probably make the size of the device too big. Assuming that these batteries can deliver around 2000 mAh (PowerStream Technology, 2017), an average current of

$$I_{avg} = \frac{2000\ mAh}{40\ d \cdot 24 \frac{h}{d}} = \frac{2000\ mA\cancel{h}}{960\ \cancel{h}} = 2.08\overline{3}\ mA$$

can be drawn from the battery. That corresponds to an average power of $P_{avg} = U_{bat} \cdot I_{avg} = 4.5\ V \cdot 2.08\overline{3}\ mA = 9.375\ mW$. As discussed under statement (8), the transmission power makes a big difference in the link quality between nodes in the WSN. When using the worldwide available 2.4 GHz band, there are no problems with 60 mW transmission power, whereas the 1 mW is not sufficient (Jedermann, Pötsch, et al., 2014; Ruiz-Garcia et al., 2008). A transmission power of 10 mW could be sufficient, however this needs to be examined further. The XBee-PRO module can transmit at 10 mW by using a maximum current of 150 mA, as well as 10 µA power consumption in sleep mode (Digi International Inc., 2009). Assuming the sensor measurements and data processing uses about 10 mA, the total maximum current is 160 mA. As the device is powered by 3.3 V, this corresponds to $P_{max} = 528\ mW$ and $P_{sleep} = 33\ \mu W$. If the device is kept in sleep mode most of the time and only woken up to measure and transmit data, the average power consumption can be kept at a very low level. The average power consumption is

$$P_{avg} = \frac{t_{on} \cdot P_{max} + t_{off} \cdot P_{sleep}}{t_{total}}$$, whereas $t_{total} = t_{on} + t_{off}$.

The time t_{on} covers the time of measurement, processing and transmission, which is difficult to determine. However, Heidmann et al. (2013) mention that their device takes about 250 ms for this process. The assumption is made that t_{on} is the same here. The equation above results in the following:

$$P_{avg} = \frac{t_{on}}{t_{total}} \cdot P_{max} + \frac{t_{total} - t_{on}}{t_{total}} \cdot P_{sleep} = \frac{t_{on}}{t_{total}} \cdot P_{max} + \frac{t_{total}}{t_{total}} \cdot P_{sleep} - \frac{t_{on}}{t_{total}} \cdot P_{sleep}$$

The fraction $\frac{t_{on}}{t_{total}}$ can also be defined as the duty cycle D, which gives the following equation:

$$P_{avg} = D \cdot P_{max} - D \cdot P_{sleep} + P_{sleep} \;\rightarrow\; D = \frac{P_{avg} - P_{sleep}}{P_{max} - P_{sleep}}$$

Using all the values from above, the duty cycle and thus the time t_{total} can be determined:

$$D = \frac{9.375\,mW - 0.033\,mW}{528\,mW - 0.033\,mW} \approx 0.01769 \rightarrow \; t_{total} = \frac{t_{on}}{D} = \frac{0.25\,s}{0.01769} = 14.13\,s$$

This means that the sensor node can measure approximately every 15 seconds in order to keep the average power consumption under the threshold of 9.375 mW to maintain a battery life of 40 days or more. Note that this doesn't take into account the voltage drop of the battery and other inefficiencies, such as the efficiency of the voltage regulator. To sum up, besides using low-power communication technology, such as IEEE 802.15.4, it is also recommended to use power-saving algorithms, such as programmable duty cycles of devices to keep the power consumption as low as possible. A programmable duty cycle can also be used to find a compromise between battery life and sample rate and thus it can be tailored to the specific requirements of the consignment. Of course, it can be argued that a larger battery can simply solve the problem of battery life. However, the size and maintenance of the devices also need to be considered. The batteries should be widely available, cheap and easy to replace and keep the device light and small in size. Therefore, the calculation above was based on the capacity of AA batteries. It would be even more preferable to use AAA batteries because of the smaller size and weight. However, the capacity would only be a third to a half, compared to AA batteries (RightBattery.com, 2013). The effect of temperature on the battery life has not been considered in the calculation. Experiments should be conducted to test it in a real scenario.

Statement 10

Statement (10) suggests that sensor measurements should fulfill guidelines prescribed by standards for goods transportation. As an example, the standard for food distribution BS EN 12830 is used, which concerns the temperature recordings for the transport, storage and distribution of food in the cold chain. The following requirements are defined in the standard (Lascar Electronics, 2017) among others:

- The measuring range should at least cover -25 °C to +15 °C.

- Accuracy and resolution of temperature measurements should be ±1 °C and ±0.5 °C respectively.
- The measurement interval should be 60 minutes for consignments longer than 7 days, 15 minutes for 1 to 7 days, and 5 minutes for less than 24 hours.

It needs to be ensured that selected sensors meet these requirements. Further examination should show if there are other standards regarding the transportation of goods that monitoring system have to comply with.

Statement 11

Statement (11) states that when the monitoring system detects that environmental conditions are not met, it should be possible to define, which company is responsible for the potential damage. As of today, independent surveyors are hired that inspect the cargo and make a statement about the reasons for the damaged goods. If the monitoring system should take over this function, it needs to be clearly defined what conditions can be provided by the carrier. This should include information about allowed temperature variations inside the container, allowed magnitudes of vibrations and physical shock, as well as other parameters. Furthermore, it needs to be documented which companies are involved in the transportation process and at which time, e.g. for loading/unloading procedures. If this is ensured and requested conditions are defined clearly, the monitoring system can identify when conditions are violated and at which time and can thus determine who carried the responsibility at this specific time. This approach could decrease the necessity for inspections. However, more insights into the administrative aspect of a transportation process should be gained to validate the approach.

Overview

The table below shows an overview of all the analyzed requirements. The ones that don't fulfill the assessment, are either not clear, complete or implementable with the available information (cf. chapter 3.4.4). These requirements need to be revised after gathering more information about the issues they concern. Furthermore, the requirements care categorized into functional and non-functional requirements (cf. chapter 3.4.1).

Table 4 - Overview of system requirements

#	Requirement description	Fulfill assessment?	Category
01	Costs of monitoring system must be lower than today.	*no*	Non-functional
02	Real-time monitoring requires satellite network connection in remote areas (e.g. on open ocean). Local network on vehicle is required, so that staff can be alerted if conditions are not met. The central node (gateway node) of the WSN (cf. Figure 14) should provide a flexible solution for choosing between a mobile network module or satellite network module.	yes	Functional
03	The logistics of monitoring equipment has to be ensured.	no	Non-functional
04	The sensor nodes should provide physical interfaces for pluggable sensor modules. Sensor modules should be equipped with the same physical interface, so that they can be plugged into the nodes. The WSN should support 105 nodes.	yes	Functional
05	The system should help documenting processes to satisfy regulatory requirements.	no	Functional
06	The geographical location of the cargo should be determined, either via cell ID positioning over the mobile network or via GPS.	yes	Functional
07	Ten to 60 sensors are required to capture temperature differences inside a container, depending on the level of detail needed by the customer.	yes	Functional
08	A reliable communication inside the container requires a transmission power of 10 mW.	yes	Non-functional
09	The battery life of devices should cover at least the length of one consignment, estimated to be 40 days including buffer. Therefore, the use of low-power IEEE 802.15.4 technology and power-saving algorithms is required, such as a programmable duty cycle of measurements should be implemented.	yes	Non-functional
10	It is required that sensors meet the requirements of standards for goods transportation, such as BS EN 12830	no	Non-functional
11	Defining the responsibility in case of comprised food safety and quality requires a clear agreement on the conditions inside the container (limits of all monitored parameters), as well as documentation of responsibilities in all time periods.	no	Functional

5.1.2 From system requirements to system component requirements

Table 4 in the previous section shows the analyzed requirements that were extracted from the interviews and literature review. These form the system requirements. However, only the ones that fulfill the assessment can be further analyzed, the ones not fulfilling the assessment must be revised before.

The following list shows the requirements to be analyzed further.

1. The gateway node has to offer an interface for a pluggable mobile network module or satellite network module.
2. A local network on the transportation vehicle should be used to alert staff if required environmental conditions are not met.
3. Sensor nodes should provide interfaces for pluggable sensor modules, such as temperature, humidity, physical shock, light intensity, CO_2, O_2 and ethylene concentration.
4. 105 sensor nodes in one container should be supported by the wireless sensor network.
5. Geographical location should be able to be determined, either via cell identification or via GPS, depending on which network module is used on the gateway node.
6. At least ten to 60 sensors should be used inside the container in order to monitor temperature variations.
7. The IEEE 802.15.4 standard shall be used, with a frequency of 2.4 GHz and transmission power of 10 mW.
8. The battery life should be at least 40 days. This can be achieved by using power-saving algorithms.
9. A variable duty cycle should be possible, so the battery life can be extended if necessary.

Assessing these requirements, they satisfy statement (2), (4), (6), (7), (8) and (9) listed in the previous section and each of the new requirements satisfies at least one input requirement. The requirements of the previous section that are not satisfied, are the ones that needs to be revised as described before.

The new requirements can be analyzed even further, so that specific requirements for the components of the system can be defined. The components of the system are mainly the sensor nodes, responsible for measuring the conditions inside the container, as well as the gateway node, responsible for collecting the data and forwarding it to the remote server, and for determining the geographical location. Furthermore, the container and the transport vehicle itself are components of the system. It is where the nodes of the wireless sensor networks are deployed. The remote server, including the user interface and database, are also part of the system. However, as this report focuses on the wireless sensor networks, the requirements here only concern the sensor and network layer of the system.

Table 5 below shows the requirements for the components of the monitoring system, not taking into account the requirements in the previous section that need to be revised.

Table 5 - Overview of system component requirements

Com-ponent	Requirements
Sensor node	• The sensor node should contain a communication unit based on IEEE 802.15.4 using the 2.4 GHz ISM band. • The transmission power of the communication unit should be 10 mW. • The sensor node should provide interfaces for different types of sensors that can be connected to the node in a plug-and-play way (temperature, humidity, physical shock, light sensitivity, CO_2 concentration, O_2 concentration, ethylene concentration). The CPU of the node should therefore automatically recognize the sensor units and process measured data. • The battery life should be at least 40 days, running on widely available and small batteries, such as AA or AAA batteries. The use of power-saving algorithms should be used. • The sensor node should have a variable duty cycle for measurements and transmission of data.
	Satisfies system requirements (3), (7), (8), (9)
Gateway node	• The gateway node should provide an interface for connecting a mobile network module or satellite network module in a plug-and-play way. The CPU of the node should automatically recognize the network unit. • The gateway node should be able to connect to a local network provided on the transport vehicle, so it can alert staff if required conditions are not met. • The gateway node should be able to handle the communication of 105 sensor nodes. • The gateway node should determine the geographical location, based on cell localization or GPS, depending on what network module is used.
	Satisfies system requirements (1), (2), (4), (5)

Transport vehicle	• The transport vehicle should provide a local network that the gateway node can connect to in order to alert staff on the vehicle (driver, engineers, etc.).
	Satisfies system requirement (2)
General	• In order to measure temperature variations at different locations inside the container, ten to 60 sensor nodes should be used, depending on the required level of detail.
	Satisfies system requirement (6)

5.2 Cost-and-benefit analysis

One of the most important factor that affects the decision for a particular monitoring system, are the costs of the system, as well as the benefits it can bring. Therefore, an separate chapter is dedicated to this issue. The methodology of conducting the cost-benefit analysis is described in chapter 2.3.

5.2.1 Specify alternative projects

First of all, alternative projects need to be specified so that the costs and benefits can be compared with an alternative. In this CBA, the first alternative is a monitoring system based on the requirements presented in the previous section, with multiple sensor nodes distributed in the container, hereinafter referred to as multi-level monitoring system. The second alternative is a monitoring system that is currently used in the industry with only one sensor device per container, hereinafter referred to as industrially used monitoring system. The MOST system with a one-way model is used as an example for a currently used system (cf. chapter 3.3.6).

5.2.2 Determine the stakeholders whose costs and benefits should be taken into account

In the interview with Kuehne+Nagel, the main stakeholders of a transportation transport were identified as being the consignee, the carrier, consignor, as well as the freight forwarder. The consignor is the company, whose goods are being transported to the consignee. The consignor usually hires a freight forwarding company that organizes and takes care of the entire consignment. The freight forwarder may transport part of the whole consignment with own resources, as well as uses the services of carriers to transport the cargo.

Another important stakeholder, even though not a legal person, is the environment because a monitoring system has a direct impact on the environment. However, it is very difficult to assess the impact on the environment and Boardman et al. (2006) states that only impacts, where there is the knowledge to carry out a rational valuation, can be assessed in the CBA and generally only impacts that affect human beings are taken into account. Therefore, it is not taken into calculation, but it should be kept in mind that there are other impacts and that a CBA cannot reflect all costs and benefits.

Other stakeholders that are not directly involved in the process are regulatory agencies that check whether the consignments have been conducted appropriate according to regulatory requirements. Furthermore, the society is a stakeholder because it can benefit from improved product quality. Other than that, the provider of electronic components as well as the provider of mobile and satellite networks benefit from the production and use of monitoring devices.

The cost-benefit analysis only includes the costs and benefits of the main stakeholders because it is difficult to estimate the impacts for other stakeholders.

5.2.3 List the costs and benefits

There are several costs and benefits that affect the different stakeholders of a monitoring system. Obviously, there are development costs and the costs for manufacturing the electronic monitoring devices. Furthermore, there are several running costs, such as costs for servers and network costs for mobile or satellite networks. Other than that, there are costs related to maintaining and handling the devices. The devices have to be attached to transport boxes and batteries need to be replaced after a journey. Additionally, when devices are broken or if they are only used for one journey (as for the industrially used system), there is an additional cost of disposing of these devices.

On the positive side, there are various benefits compared to not having a monitoring system in place. There is likely a reduced number of items that have been destroyed or that perished during the transportation. A monitoring system can give evidence about which party is responsible if a damage occurs, and thus decreasing the necessity of having negotiations and surveyors inspecting the cargo, whereas this will probably never be completely redundant. Other benefits are a higher product quality and thus a higher customer satisfaction, as well as possibly higher prices. A monitoring system also increases transparency, which leads to a better reputation of the shipping company. Furthermore, there is a potential for optimizing the packing and loading processes because a monitoring system could help to detect the occurrence of blocked airflows leading to less efficient temperature control, which is often caused by not ideal loading of the cargo. Real-time monitoring would allow consignees to reorder products faster when they can see that their cargo is in insufficient condition. Table 6 gives an overview of all the mentioned costs and benefits.

Table 6 - Costs and benefits of monitoring system

Costs	**Benefits**
Costs for hardware and software • Development costs (hardware + software) • Manufacturing costs • Server costs • Network costs (mobile/satellite network) Costs for handling devices • Attaching devices to transport boxes • Sending devices to next deployment site Maintenance costs • Replacement of broken devices • Replacement of batteries Other costs • Electronic waste (disposal of devices)	Improved product quality • Reduced amount of defective/perished goods ➔ higher number of sold products ➔ lower cost of disposing of defective cargo • Better quality of products ➔ higher customer satisfaction ➔ higher prices Improved transparency • More transparency of transportation process ➔ Better reputation of carrier • Clearer assignment of responsibilities ➔ Less involvement of surveyors and less negotiations Optimization potential • Potential to optimize packing and loading processes because monitoring system can detect blocked airflows, etc. • Other optimization potential (e.g. fleet management, reduced waiting times, etc.) Other benefits • Real-time connectivity allows consignees to reorder faster if products are not in sufficient conditions

5.2.4 Quantify costs and benefits and assign a monetary value to the impacts

In order to quantify the costs and benefits, a specific transportation scenario has to be chosen, so that valid assumptions can be made about the impacts. A few scenarios are described in the articles that have been presented in chapter 4.2. Therefore, the information of these scenarios can be used in the cost-benefit analysis. One scenario is chosen, which is presented below, along with the made assumptions.

Scenario: Transoceanic transport of lemons

The scenario is based on the experiment described by Jiménez-Ariza et al. (2014). The experiment had the following relevant characteristics:

- 25,000 kg transported from Montevideo, Uruguay to Murcia, Spain
- Duration: 31.7 days (22.2 days in transoceanic ship, 9.5 days in second vessel, 2 h in truck)
- 20 pallets x 80 boxes

The following assumptions are made about the multi-level monitoring system:

- Use of 60 sensor nodes (3 per pallet on different heights) + 1 gateway node
- Manufacturing costs: 12€ per sensor node and 86€ per gateway node[2]
- Devices have to be replaced every 5 years (10 journeys per year) ≙ 50 consignments
- Use of satellite network communication at $1 per MB (Tuczynski, 2009), equaling 0.85€ at current exchange rate.
- Gateway node sends HTTP requests to remote server every 15 minutes, totaling 12 kB[3] for all 60 sensor nodes. This results in 1.152 MB per day.
- The sensor nodes are powered by three AA batteries each.

The following assumptions are made about the industrially used monitoring system:

- Total hardware and software costs are $55, which is the price per device (Miovic, 2018), equaling 47€ at current exchange rate.

[2] Based on de la Fuente Ruz et al. (2007), who present a similar monitoring system

[3] The data string in chapter 6.1.2 is about 100 Bytes, which would be 6 kB for 60 nodes. 12 kB is used here as an assumption that includes overhead.

Hardware and software costs

The hardware and software costs comprise four different costs as it can be seen in Table 6 above. However, here only the component costs and the network costs are taken into account. The development cost is neglected despite its high amount because it is an initial cost that has a big impact in the beginning of a project or for a project of small scale. However, it is assumed that monitoring systems are widely used, and the impact of the development costs are negligible for that reason. The same goes with server costs that are required to host the monitoring platform. The costs are attributable to all consignments. Server costs can be as low as 5€ per month and the higher the scale of the monitoring system, the lower the costs per consignment. Therefore, these costs are also negligible for this analysis.

The manufacturing costs of the devices are stated above. When 60 sensor nodes and one gateway node is required, the costs are 806€. As the nodes can be used for 50 consignments on average, the manufacturing costs per consignment are $C_{manufact,1} = \frac{60 \cdot 12\text{ €} + 86\text{ €}}{50} = 16.12\text{ €}$. The network costs can be calculated by multiplying the duration of the trip with the daily data usage and the cost per data unit, resulting in $C_{network,1} = 31.7\ d \cdot 1.152\ \frac{MB}{d} \cdot 0.85\ \frac{\text{€}}{MB} = 31.04\text{ €}$. Both costs together yield total hardware and software costs of 47.16 €.

Handling costs

The handling costs include the attachment of devices to the transport boxes, which is assumed to take 0.5 minutes per node. An average salary of a logistics worker in the UK is about 20,500 € annually (reed.co.uk, 2017), which is taken here as an example. At about 45 weeks of 40-hours week, this is a wage of approximately 11.4 € per hour, which is certainly an above-average wage in this industry globally. Additionally, there is the need to transport devices to the next deployment site, unless they can be reused at the same location. This is not a cost for the industrially used monitoring system because it is only used one-way and disposed after one journey. For the multi-level monitoring system, 61 devices would have to be sent. Assuming that the system's use is widespread, and devices can always be reused within country limits, national package costs can be kept at about 25€ or lower, by comparing prices of DHL for example. This means that the handling costs for the multi-level system are $C_{handling,1} = 61 \cdot 30\ s \cdot 11.4 \frac{\text{€}}{h} + 25\text{ €} = 30.8\text{ €}$, while the handling costs for the industrially used system are only $C_{handling,2} = 30\ s \cdot 11.4 \frac{€}{h} = 0.095\ €$ for attaching the one device to the container.

Maintenance costs

The maintenance costs include the replacement of batteries and the replacement of broken devices. The maintenance costs for the industrially used system are zero because it is only used one way and neither batteries nor broken devices have to be replaced for that reason.

For the multi-level system, AA batteries are required. The cost of qualitative AA batteries is about 0.1 € per battery, looking at common resellers (e.g. rs-online). 60 devices times three batteries are 180 batteries needed in total, which is a cost of 18 €. The replacement of broken devices is already taken into account in the manufacturing costs above because it is assumed that devices can be used for 50 consignments on average. Therefore, the total maintenance costs for multi-level monitoring is 18 €.

Other costs

Other costs include the disposal of devices. The cost of electronic waste is assumed to be $360 per ton (Struthers, 2016), which corresponds to 308 € per ton, or approx. 0.31 € per kilogram. The MOST devices (cf. chapter 3.3.6), which is the example for the industrially used monitoring system, weighs about 220 g (Miovic, 2018). This weight is also assumed for the gateway node of the multi-level monitoring system. The sensor nodes are more light-weight, the weight of the proof of concept node is used as an example (see chapter 6), which is about 50 g.

The industrially used monitoring system device has to be disposed after each consignment. Therefore, the cost is $C_{disposal,2} = 0.22\ kg \cdot 0.31 \frac{€}{kg} = 0.068\ €$. The devices for the multi-level monitoring system can be reused for 50 consignments on average. Therefore, in order to calculate the costs for one consignment, the costs of disposal should be divided by 50. The costs are $C_{disposal,1} = \frac{(0.22\ kg + 60 \cdot 0.05\ kg)}{50} \cdot 0.31 \frac{€}{kg} = 0.02\ €$.

Improved product quality

One benefit of monitoring systems is an improved quality of the cargo. This results in fewer product losses, which has a positive effect on the number of products that can be sold and number of products that have to be disposed. Furthermore, a higher product quality in general raises customer satisfaction and possibly higher prices can be charged.

Wholesale prices of lemons from South America show large price differences from about $100 to about $2000 per ton (on www.alibaba.com), with most offers being around $500 per ton. Therefore, $500, or 427 €, is the assumed price for the lemons in this transportation scenario, while the assumed price for food waste is $40 per ton (Struthers, 2016), or 34€. Regarding food losses, they vary between 5% and 25%, depending on the region and type of product (Jedermann, Nicometo, et al., 2014). Therefore, 15% is assumed for losses of lemons without the use of monitoring systems. With the use of the industrially used monitoring system, losses are estimated to be marginally lower, about 13%. The quality of products can hardly be determined with only one device per container, which is an important indicator to optimize processes and reduce losses (Jedermann, Nicometo, et al., 2014). Regarding the multi-level monitoring, Reiner Jedermann et al. (2014) reported different studies that showed the reduction of losses due to optimization by use of shelf-life information and other quality information, e.g. reduction of losses from 37% to 23% for strawberries, 17% to 4% for pork meat, and 15% to 5% for sea bream. Based on this information, optimization with the help of the multi-level monitoring information is assumed to lower losses from 15% to 8%. Table 7 shows an overview of the spoilage of lemons with and without the use of a monitoring system.

Table 7 - Product losses with and without monitoring

	Lemons lost in %
Without monitoring	15 %
Industrially used monitoring	13 %
Multi-level monitoring	8 %

This results in 3,750 kg of lemons lost without the use of a monitoring system. With the use of the industrially used monitoring system, losses can be reduced by 500 kg, which means 500 kg more lemons can be sold and the same amount has to be disposed less. This is a benefit of $B_{quality,2} = 0.5\ t \cdot 427 \frac{€}{t} + 0.5\ t \cdot 34 \frac{€}{t} = 230.5\ €$.

For the multi-level monitoring system, only 2,000 kg of lemons are spoiled, compared to 3,750 kg. This a reduction of 1,750 kg. The benefit in higher product quality is therefore $B_{quality,1} = 1.75\ t \cdot 427 \frac{€}{t} + 1.75\ t \cdot 34 \frac{€}{t} = 806.75\ €$.

The benefit of higher customer satisfaction and the possibility to charge higher prices is difficult to quantify and therefore not taken into account here.

Improved transparency

Increased transparency helps to improve the reputation of the carrier, which makes it easier for consignors and consignees to choose a carrier when they can see how reliable different carriers are. However, the impact of this benefit cannot be estimated, which makes it very difficult to quantify this benefit. Therefore, it is disregarded in this analysis.

The same applies to the benefit of increased transparency of responsibility, which means the monitoring system could determine, which party is responsible if an incident happens and thus lower the necessity for having an expert opinion and negotiations. However, to what extent that would be true, needs to be determined in the future. Therefore, it is also disregarded in this analysis.

Optimization potential

Monitoring systems have the benefit of enabling carriers to potentially improve their processes. Monitoring can provide valuable data, for example about which part of the container is not cooled down efficiently, which could be traced back to improper loading and packing of the cargo. Other potential optimization could be for example the reduction of waiting times at ports, when the locations of containers are known at any time. This benefit has already been taken into account in the section about improved product quality above.

Other benefits

Other benefits are that real-time connectivity allows the consignee to see the conditions of the cargo at any time and enables him to reorder products a lot faster as soon as the monitoring determines insufficient condition of the goods. If no real-time connectivity is available, the consignee would only see the conditions of the goods upon arrival. This gives the consignee the advantage over other distributors to react faster, which makes the supply chain more flexible.

According to Sun and Goldbach (2013) of PricewaterhouseCoopers, supply chain flexibility is one of the highest priorities among companies. But as with most of the other benefits, it is really difficult to quantify this benefit and assign a monetary value to it because it depends on many factors that are not known and that can vary in a large range. Therefore, it is not of advantage to quantify it here.

Table 8 below shows an overview of all presented costs and benefits for the described scenario. Even though most of the benefits could not be quantified and many assumptions had to be made, the cost-benefit analysis gives a tendency what value currently used monitoring systems and more advanced monitoring systems can bring.

Table 8 - Monitoring system cost-benefit analysis

	Alternative 1 **Multi-level monitoring**	Alternative 2 **Industrially used monitoring**
Costs Hardware and software costs Handling costs Maintenance costs Other costs	 47.16 € 30.80 € 18.00 € 00.02 € **95.98 €**	 47.00 € 0.10 € - 0.07 € **47.17 €**
Benefits Improved product quality Improved transparency Optimization potential Other benefits	 806.75 € - - - **806.75 €**	 230.50 € - - - **230.50 €**
Net benefit	**710.77 €**	**183.33 €**

5.2.5 Calculate the net benefit of each alternative

The net benefit is simply the value of benefits minus the costs. The calculated net benefits of both alternatives are presented in Table 8. It shows that a multi-level monitoring system can provide more value to all stakeholders than a container-level monitoring system as it is commonly used in the industry today. And this calculation does not take all potential benefits into account, so the net benefits can be even higher than shown here.

On the other hand, the benefits depend to a great extent on the value of the transported product and how well the monitoring system can assist to reduce product losses. By varying the parameters in the calculation under *Improved product quality*, even small improvements can provide large benefits. In the example, the industrially used monitoring system reduces losses by two percentage point, while the multi-level system reduces losses by seven percentage points. Even a reduction of one percentage point has a benefit of over 100 €, which outweighs the costs. However, if the price for lemons would be a fraction of the assumed price, the benefits diminish quickly. Therefore, the net benefits greatly depend on the transported product, the obtained results in terms of reduced product spoilage and the value of the product.

5.3 Limitations

The requirements engineering process used in this project is a bit different than regular approaches. It is beneficial to involve all stakeholder groups and multiple representatives from each stakeholder group. However, interviews were only conducted with one stakeholder group. Furthermore, only three companies agreed to participate in an interview, whereas over 15 companies in the transportation industry were contacted. Other companies were not willing to participate in interviews or simply did not respond, even after multiple contact attempts.

Moreover, as requirements engineering is usually an iterative process, it is recommended to have a closer interaction with the stakeholders so that the requirements can be more clearly defined in iterative interviews. However, it was not possible to schedule additional meetings with the interviewed companies in the given period. It was a very time-consuming process to agree on meetings in the first instance, which was a time factor that was not taken into account. Furthermore, some of the requirements are not clear enough and need to be specified clearer, in order to be implementable. It requires further interviews with the stakeholders in order to gather more information and clarify, how these requirements can be addressed, e.g. regulatory requirements.

Regarding the cost requirements, companies stated that the costs of monitoring are too expensive today. It is unclear what that specifically means to them and it would have been good to gather specific information about their costs. However, they were not able or willing to share information regarding specific costs. A more general cost-benefit analysis has been conducted to give a general overview of costs and what impact they have in a specific scenario.

In the cost-benefit analysis, several assumptions had to be made that can vary in a big range, such as the price of lemons discussed above: the maximum price was about 20 times higher than the minimum price. As shown, the price of the transported goods is one important factor that determines whether the use of a monitoring system is of benefit or not. Therefore, it cannot be claimed with certainty that the use of a multi-level monitoring system is beneficial or not, but it has to be tested and assessed on a case-by-case basis.

6 Proof of concept

The purpose of the proof of concept is to demonstrate the feasibility of this idea with relatively cheap components. It allows monitoring the geographic location, temperature, and relative humidity in (near) real-time. The system comprises a web-based monitoring platform running on a remote server, as well as a sensor device that transmits data to that server. As this report mainly focuses on wireless sensor networks, the focus here is on the sensor device as well. Figure 15 shows the overall system architecture.

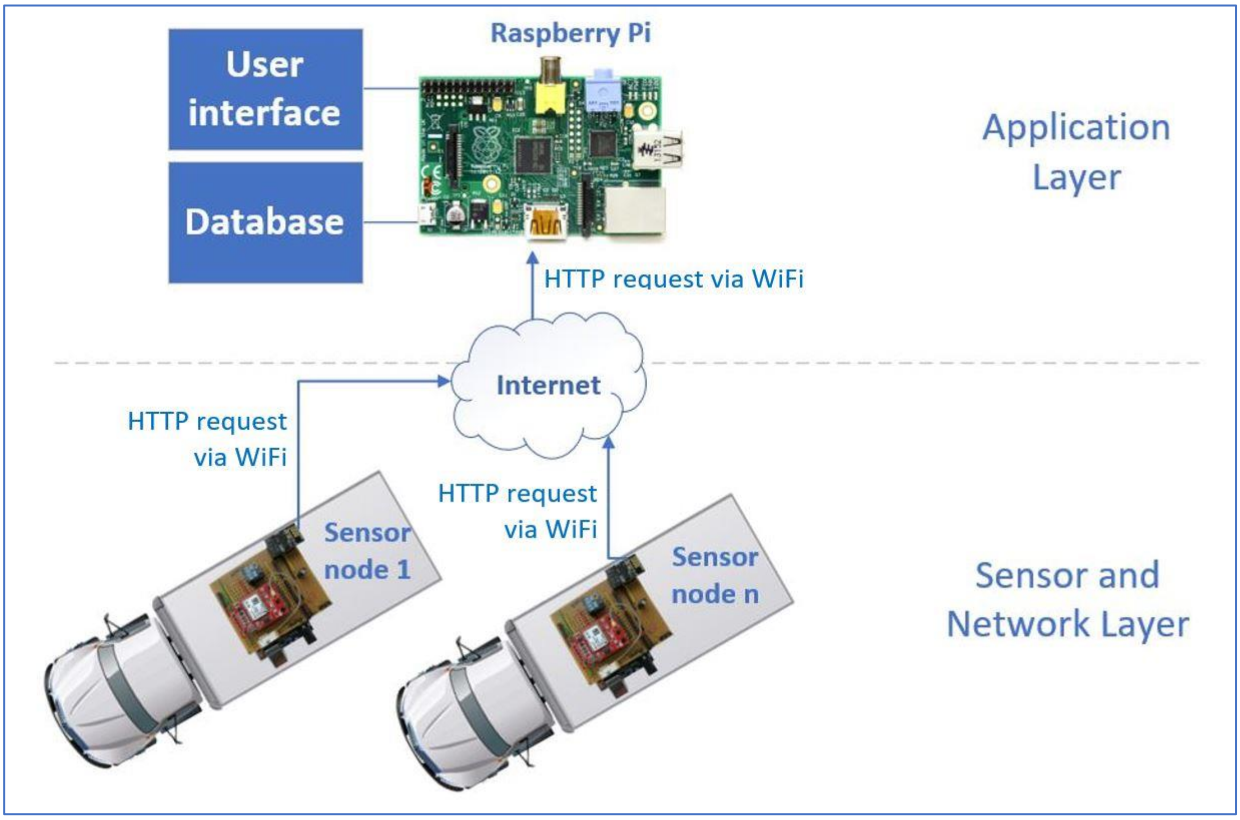

Figure 15 - Proof of concept: system architecture

Web-based monitoring platform

The web-based monitoring platform is running on a Raspberry Pi that runs the Apache HTTP open-source server software. The server also hosts a database, based on the open-source database management system MySQL. The Apache server allows an easy setup of PHP, which is used for server-side scripting. The reason for using these applications is mainly the familiarity of these applications from earlier projects, the simple and well-documented setup, as well as easy accessibility due to their open-source license. The Raspberry Pi is used because it is a low-cost computer that has enough computing power to run a webserver and a visual operating system, which makes it simple to set up the described applications.

With this setup, a simple platform is build up using PHP on the server side and HTML, CSS and Javascript/jQuery on the client side. The platform demonstrates how different consignments can be organized and how measurements can be accessed, when one particular consignment is selected. The platform connects to two different Google APIs for visualizing the measurements. These are Google Chart API in order to show temperature and humidity values in a chart over time and Google Maps API in order to show the geographical route that was taken. Figure 16 below shows a screenshot of the location monitoring of a shipment. It visualizes the transport route on Google Maps, retrieved by the Google Maps API.

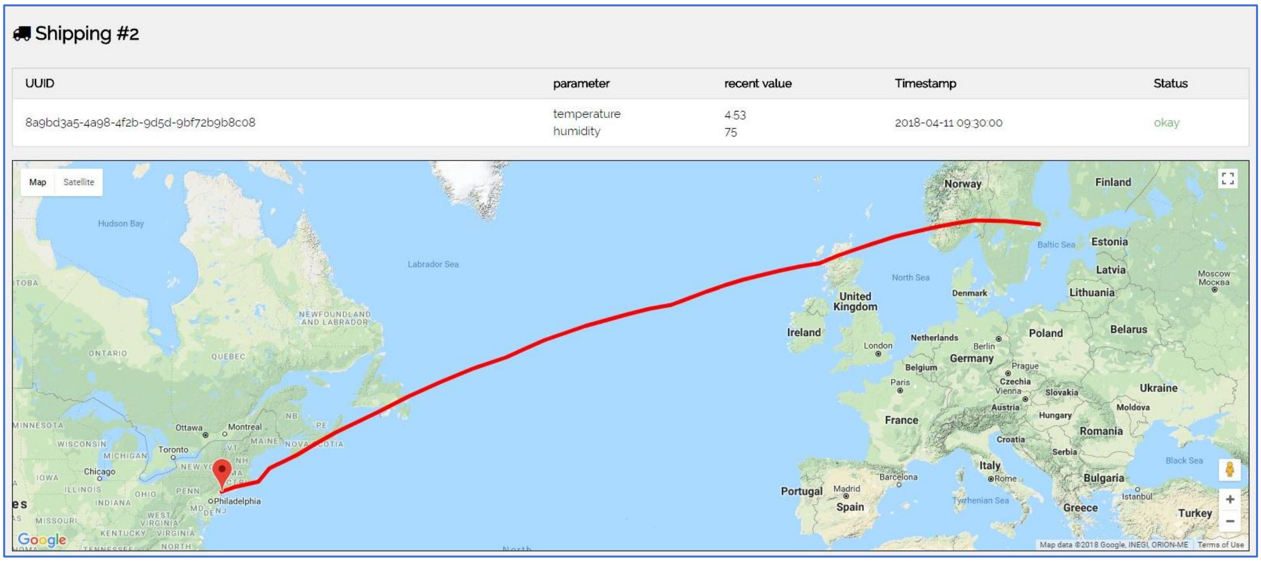

Figure 16 – Proof of concept: Screenshot of monitoring UI

Wireless sensor device

The wireless sensor device comprises of different components and is based on the electronic prototyping platform Arduino. As described in chapter 3.2.1, a wireless sensor consists of at least a processing unit, a sensor unit, a communication unit, and a power supply.

At its heart, the sensor device runs an ATmega328P, which sits on the Arduino UNO board and is a very commonly used and available microcontroller. It is the processing unit that contains the implemented software and thus, coordinates all the other components.

There are two sensor units implemented into the wireless sensor device. First of all, an HTU21D, which is a one-chip relative humidity and temperature sensor, as well as a NEO-6M GPS module. With these sensor units, it is possible to measure the temperature and relative humidity of the air, as well as retrieving the geographical location of the sensor device in specific time intervals, set in the software. In order to communicate with a server, a wireless communication module is necessary. Therefore, the low-cost WiFi chip ESP8266 is used. It is used to make HTTP requests to the server and therefore transmit the sensor data wirelessly.

As the sensor device is built up in a very modular way, it could simply be extended by a range of other sensors or the communication modules could be exchanged.

6.1 Development of the wireless sensor device

This subchapter describes the development of the sensor node from a hardware and software perspective.

6.1.1 Hardware

The main requirements of developing the sensor nodes were that it should be simple, information and components should be widely available, and it should be low-cost. The decision fell on Arduino as the prototyping platform because it offers a wide range of available software libraries for many different components, such as sensors and wireless communication modules. As this project has strict time limits, this was very beneficial because it made the software development simpler compared to other microcontrollers, and thereby faster. Furthermore, the Arduino platform is based on the widely available *ATmega* microcontroller family, which makes it a very low-cost component. The Arduino board functions as the CPU of the sensor node.

The sensor node contains three main components besides the Arduino board. These are an integrated temperature and humidity sensor (HTU21D), a GPS module (NEO-6M), and a WiFi module (ESP8266), as described above. Thus, it can measure temperature, relative humidity, and determine the geographical location of the device. The WiFi module is the communication module of the sensor node and enables it to join a wireless local area network (WLAN) and send requests over the network. The sensor node is a stand-alone device that can directly communicate over the internet. However, it requires the presence of a WLAN. This is mainly for demonstration purposes.

In a real transportation setting, the WiFi module could be replaced with a mobile network module, featuring 3G or 4G communication, and thus enable the communication over the internet without an existing WLAN.

The three modules all require a 3.3V supply, whereas the Arduino works with 5V. The Arduino UNO board that is used, contains a voltage regulator, so that even higher voltages up to 12V can be supplied. The sensor node was designed as an extension board for the Arduino. It can be simply plugged onto the Arduino. Figure 17 shows the Arduino UNO board alone, as well as the complete sensor node and Figure 18 shows the circuit layout of the sensor node extension board. Because of the different supply voltages, the voltage regulator AP1117 was used on the extension board, to lower the voltage supplied through the Arduino board to 3.3V. Two capacitors C1 and C2 on the board ensure the stability of the voltages. The capacities used are recommended in the datasheet of the used voltage regulator. The pins of the ESP8266 and NEO-6M that are not connected to the circuit, are not required for this application.

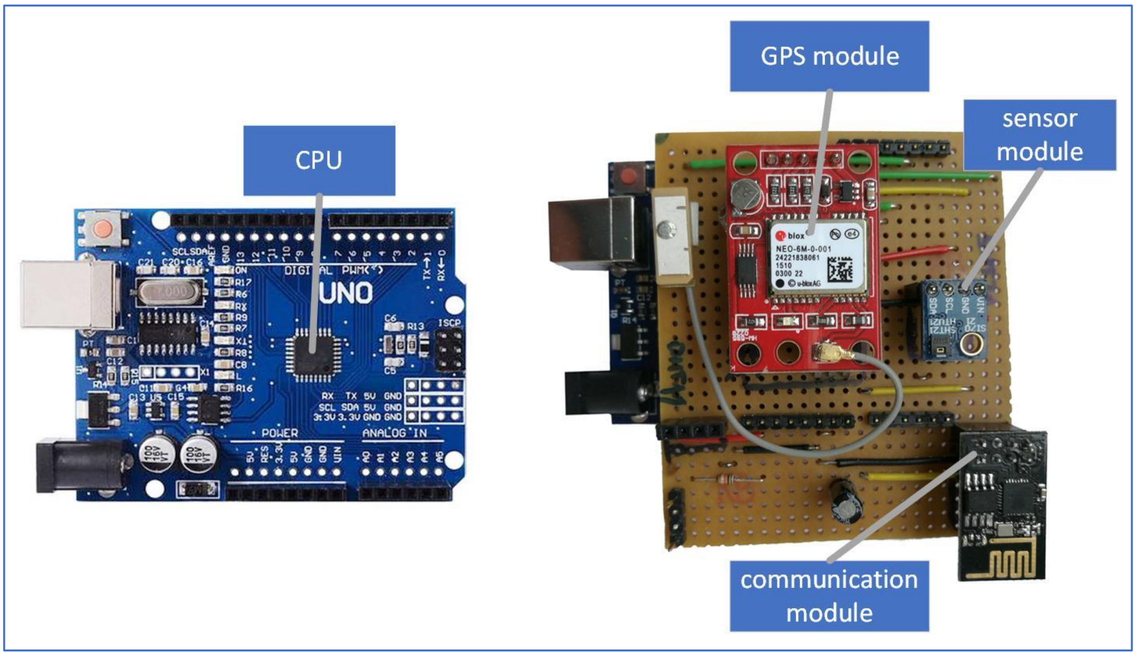

Figure 17 - Arduino UNO (left) and sensor node (right)

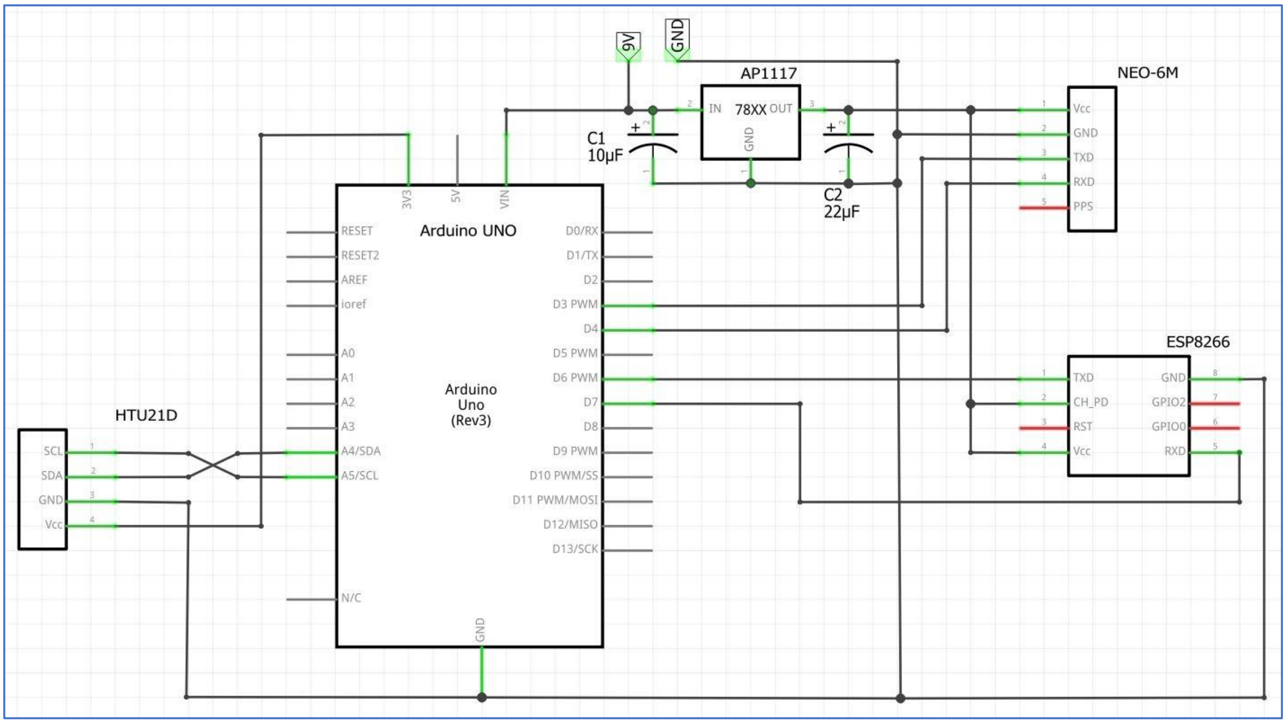

Figure 18 - sensor node circuit layout

The temperature and humidity sensor (HTU21D) communicates over the I^2C interface with the CPU (Arduino UNO), whereas the communication module (ESP8266) and GPS module (NEO-6M) communicate over an asynchronous serial communication with it. The CPU functions as a coordinator between the modules and processes the data. The implementation of the communication is shown in the following chapter.

Power consumption

In order to determine the power consumption of the sensor node, the power of all components need to be added together. The main components are the Arduino UNO, the HTU21D sensor, the NEO-6M GPS module, and the ESP8266 WiFi module. It is important to note that there are no power management functions implemented, and the power consumption can be greatly reduced with the use of sleep modes, and other power-saving algorithms. The power consumption of the sensor node is shown in Table 9. The values are extracted from the datasheets provided by the manufacturers, unless otherwise stated.

Table 9 - Proof of concept: power consumption

Component	Power consumption
Arduino UNO	232.5 mW (Igor, 2013)
HTU21D (temperature and humidity sensor)	0.3 mW
NEO-6M (GPS module)	128.7 mW ($3.3\ V \cdot 39\ mA$)
ESP8266 (WiFi module)	264 mW ($3.3\ V \cdot 80\ mA$)
Total	**625.5 mW**

The power dissipation of the voltage regulator is hereby not considered.

6.1.2 Software

This chapter describes the part of the source code implemented into the CPU of the sensor node that handles the transmission of data to the remote server. The full source code of the sensor node can be found in Appendix C.

The following lines show how the data is formatted and sent to the remote server via an HTTP request.

```
1 String server = "192.168.43.44";
2 String path = "/transport-tracking/insert-data.php";

  // ...

3 String data = "UUID=" + UUID + "&temperature=" + String(temperature) +
  "&humidity=" + String(humidity) + "&location=" + location;
4 Serial.println(data);
5 httpRequest(server, path, data);
```

Line 1 and 2 contain information about the remote server. Line 1 stores the IP address of the remote server in a variable. Line 2 stores the location of the page where the data is sent to via the request. In this case, it is the page *insert-data.php* in the folder *transport-tracking*. Together, they form the URI *http://192.168.43.44/transport-tracking/insert-data.php* in order to locate the destination on the network. Line 3 shows the format of the data that is being transmitted. It is stored in a variable in the format of a query string that contains four parameters, separated by ampersands. The UUID is an identifier uniquely assigned to the sensor node. The other parameters (temperature, humidity, location) contain the measured data of the sensor, as well as of the GPS module. An example of the query string could be

UUID=839bc62d-f521-4b2e-9559-76ff80130639&temperature=21.5&humidity=60&location=55.649536,12.541759

This corresponds to a temperature of 21.5 °C and a relative humidity of 60% at a geographical location of 55.649536° Northern latitude and 12.541759° Eastern longitude, corresponding to a position inside Aalborg University in Copenhagen. Line 4 shows the query string in the terminal when the sensor node is connected to a computer. This is only for debugging purposes. Line 5 calls the function that initiates the HTTP request, which is shown in the following code excerpt.

```
SoftwareSerial esp(6, 7); // RX, TX

// ...

void httpRequest(String IP, String path, String data) {
  Serial.println();
  String cmd2 = "AT+CIPSTART=\"TCP\",\"" + IP + "\",80";
  Serial.println(cmd2);
  esp.println(cmd2);

  delay(1000);

  if (esp.find("OK")) {
    Serial.println("TCP connection ready");
  } else {
    Serial.println("connection failed");
    esp.println("AT+CIPCLOSE");
    return;
  }

  delay(1000);

  String req = "POST " + path + " HTTP/1.0\r\n" +
               "Host: " + IP + "\r\n" +
               "Accept: *" + "/" + "*\r\n" +
               "Content-Length: " + data.length() + "\r\n" +
               "Content-Type: application/x-www-form-urlencoded\r\n" +
               "\r\n" + data;
  String cmd3 = "AT+CIPSEND=" + String(req.length());
  Serial.println(cmd3);
  esp.println(cmd3);
```

```
24
25    if (esp.find(">")) {
26      Serial.println(req);
27      esp.print(req);
28
29      // waiting for response
30      // ...
31    }
32  }
```

Line 1 defines the asynchronous serial communication interface between the Arduino and ESP8266 communication module. The numbers in brackets indicate the pins of the Arduino that function as the receiving (RX) and transmitting (TX) line. The function *httpRequest* in line 2 requires the three parameters, that were shown in the previous excerpt: the URI, consisting of IP address and path, as well as the query string. The *Serial.println()* commands are only for debugging purposes, showing information in the terminal. The communication module works with so-called AT commands, which were originally developed for the operation of wireless modems, which are sent over the serial communication in order to dictate the module what to do, as for instance sending an HTTP request. Line 4 shows the AT command to initiate a connection with the server on port 80, which is sent to the module in line 6. Line 10 to 16 checks whether the connection was established successfully. If this is not the case, the request has to be send again. Line 20 shows the actual HTTP request, containing information about the path, the type and size of the data and the actual data in form of the query string appended in the end. Another AT command in line 21 initiates the request by telling the module how long the HTTP request is. If the ESP8266 is ready to send, it returns an arrow in the form of a large-than symbol. If the Arduino receives this symbol (line 25), the request is sent to the module, which transmits it over the WLAN to the server. Line 29 and 30 indicate that not the complete source code is shown here. The rest of the function deals with the HTTP response and terminates the connection, which can be seen in Appendix C.

6.2 Challenges

There were different technical challenges to solve when building the proof of concept, both in hardware and software.

Table 10 shows an overview of the challenges and problems as well as a short description. Underneath, they are explained in more detail along with a description how they were solved or how they can be solved. In the detailed description, they are referred to by the numbers stated in the table.

Table 10 - Proof of concept: challenges and problems

#	Challenge/Problem description
1	When starting up the sensor node, the wireless communication module (ESP8266) became very hot.
1.1	The voltage regulator is supposed to supply 3.3 V. However, the output voltage was sometimes 3.3 V and sometimes 5 V.
2	The wireless communication module (ESP8266) and the GPS module (Neo-6M) both communicate over an asynchronous serial communication. As there is only one available software serial port on the Arduino, it is a challenge to set up both devices on the Arduino at the same time.
3	When the GPS module (Neo-6M) is connected to the Arduino and gathering data, the wireless communication module (ESP8266) refuses to send out HTTP requests anymore.
4	The GPS module (Neo-6M) often has no connectivity to satellite. Time and date can often be retrieved from the satellites, however, often not the geographical location.

(#1) After soldering all the components onto the perfboard and checking all connections and voltages with a multimeter, everything seemed to work as expected. However, one problem that occurred after soldering all the components onto the perfboard was that the ESP8266 module became very hot, far beyond the regular operating temperature. However, it did not happen all the time, which was an inexplicable phenomenon. Two possible conclusions were that either the module was defective, or the supply voltage was too high. After measuring the voltage during operation, everything seemed to work fine. However, when testing a second ESP8266 module, the problem occurred again. In this way, both possible reasons were tested. Of course, there was the possibility that both modules were defective. However, there were no other modules available to test and it seemed really unlikely that both modules have the same defect. After unsuccessfully searching the web for possible reasons, the voltage was measured again. This time, the voltage was too high (5V instead of 3.3V) after the first two measurements that showed the correct voltage.

(#1.1) It was concluded that possible reasons for this problem were most likely a defective voltage regulator or a loose connection that sometimes shorts the 5V pin of the Arduino to the output pin of the voltage regulator. Before desoldering the voltage regulator, all the connections were tested multiple times, and everything seemed to be wired up correctly. Then, a new voltage regulator was used, which was tested before and worked perfectly. After soldering it onto the perfboard however, the same problem occurred again: the output pin has a potential of 5V. After testing the board in multiple settings, both with and without the Arduino, the board appeared to work without problems if not being hooked up to the Arduino directly. It seemed to be a not explainable problem. However, after looking at all the connections of the sensor node once more, it turned out that a pin that was protruding from the Arduino was touching a solder joint on the sensor board, which shorted the 3.3V supply with the 5V of the Arduino. This only happened if the sensor board is pushed all the way down as it is shown in Figure 19. The board functions well if these pins don't touch.

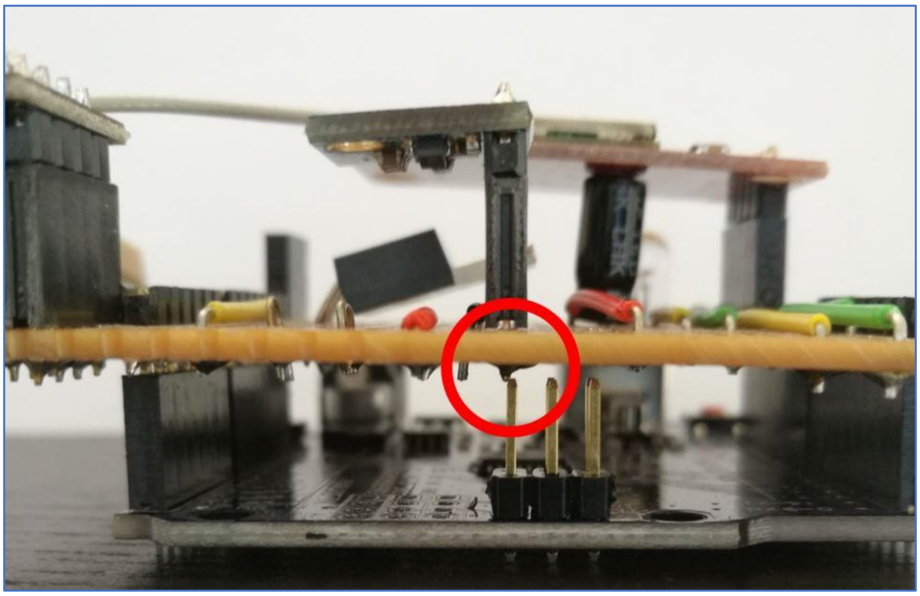

Figure 19 - Proof of concept: short circuit

(#2) The second challenge was to resolve the challenge to hook up both the ESP8266 and the Neo-6M to the Arduino at the same time. Both modules communicate over asynchronous serial communication with the Arduino. It is possible to use multiple serial asynchronous communication links. However, as the Atmega328P, the chip on the Arduino, has only one UART (Universal asynchronous receiver transmitter), they cannot be used at the same time (Atmel Corporation, 2016). Therefore, it can only communicate to the two modules in an alternating way. A software library exists for the Arduino that allows to only activate one port for the serial communication at a time, which solved the problem.

(#3) The communication to the ESP8266 with AT commands worked well when the ESP8266 was tested alone. However, together with the Neo-6M GPS module, the ESP8266 refused to execute the commands fully and it seemed that data got lost on the way. The actual reason for that is not clear but it may have to do with the fact that both modules are sharing a serial connection to the Arduino (challenge #2). However, there are multiple software libraries for setting up the communication of the ESP8266, such as the *WifiEsp* library, which handles the AT commands. However, none of these libraries worked well when the Neo-6M GPS module was connected. Data transmission over the network always failed because part of the data was lost. This was resolved by programming the AT commands directly without the help of a software library.

(#4) Another problem is that the Neo-6M GPS module has often no sufficient connectivity to the satellites in order to retrieve the geographical location. It can often gather the current time and date, but the location is determined very rarely. Only one out of more than ten tests (tested inside building) was successful, which could not be reproduced. The reason might be that the antenna’s gain is not high enough in order to retrieve the data from the satellite signals. Testing the module outside did not show any different results: location data could not be retrieved. Photos of both test setups are shown in Figure 20. Inside, the module was placed close to the window, in order to have the highest GPS signal strength. It was tested both with closed and open window. Outside, the module was tested on an open place on a sunny day with almost no clouds, thus having the best prerequisites in terms of signal strength.

Figure 20 - Proof of concept: GPS test setup

6.3 Limitations

One of the limitations of the proof of concept is that no GPS location could be determined and thus the device could not be located through the monitoring system. Unfortunately, the reason for this behavior could not be ascertained. Further tests should be conducted with a different GPS antenna, or a different GPS module.

Moreover, the proof of concept uses a WiFi module and therefore requires a wireless network in order to communicate to the remote server. It would be better to use a mobile network module, so that it could communicate from anywhere using the 3G or 4G mobile telecommunications standard.

Furthermore, the power consumption of the device is not very efficient. The WiFi module and the GPS module both use a lot of power, as shown in chapter 6.1.1. The Arduino UNO's power consumption is very high, too. Additional components on the Arduino board are using a lot of power, such as LEDs. The chip on the board, the ATmega328P has with 0.2 mA in active mode, according to the datasheet, a much smaller impact. Furthermore, if a mobile network module was used instead of the WiFi module, the location of the device could be determined by using mobile cell localization and the GPS would not be needed, providing that the required accuracy is only up to a few kilometers (Z. Zhang et al., 2009). The literature review showed that many of the described solutions use power management algorithms to decrease the overall power consumption of sensor nodes, such as setting the device into sleep mode for the inactive time, which could be implemented as a next step.

7 Discussion

In the problem formulation, the question was raised what are the requirements, costs and benefits of a wireless sensor system for the purpose of monitoring perishable goods transportation. The focus has been on four different aspects, which are discussed in this section: design and deployment, communication, power supply, costs and benefits. Additionally, the material flow was considered an important aspect, which was discovered during the project.

7.1 Design and deployment of sensor system

In terms of design and deployment of wireless sensor systems, it is important to take into account what parameters should be monitored and where sensors should be placed in order to measure the goods' condition accurately, while not compromising other requirements too much. Temperature has been determined as the most important parameter to determine the shelf life of perishable goods, whereas other parameters, such as humidity and air composition, can also play an important role. The challenges of temperature variations in containers, and sensor placement are discussed here.

Temperature variations

The literature review showed that temperature is the most important factor in transportation when it comes to the quality of food products and the interviews confirmed that temperature monitoring is of high importance, but the companies did not report problems due to inadequate temperature conditions. Research shows however that temperature control systems of reefer containers are not very efficient and temperature differences of multiple degrees are likely inside the container. Jiménez-Ariza et al. (2014) reports temperature variations at different locations in the container at the same time were up to 6.6 °C. Santa et al. (2012) reports similar problems. This is one of the reasons for the deterioration of food quality (Jedermann, Nicometo, et al., 2014; Jiménez-Ariza et al., 2014). It seems that transportation companies today are not aware of this problem, which is probably due to the fact that industrially used monitoring systems only measure temperatures at one place inside the container and don't take into account temperature variations.

Kuehne+Nagel reported in the interview that improper packing of the products is one of the main reasons for food waste during transportation. Jedermann et al. (2014) states that based on a case study on sea transportation of bananas, the cooling efficiency could be optimized up to 50% with improved packing and loading of the cargo. There seems to be some correlation between loading schemes and the efficiency of temperature control. Improper loading of cargo can for instance confine the airflow in the container, which leads to larger temperature heterogeneity inside the container (Bijwaard et al., 2011; Jedermann, Nicometo, et al., 2014; Jiménez-Ariza et al., 2014).

Sensor placement

Another challenge for monitoring systems and also related to the packing and loading of cargo is the placement of sensors. In terms of accurate shelf life prediction, it is obviously most reasonable to measure temperature, humidity and other relevant parameters right next to the product. However, this is often not feasible because of several reasons. One reason is that the radio signal attenuation is higher inside pallets and packaging (Jedermann, Nicometo, et al., 2014; Ruiz-Garcia et al., 2008), which would require a higher transmission power. This on the other hand is however detrimental to a low power consumption, which is an important requirement for transport monitoring systems. High signal attenuation is especially true for cargo with high water content. As described in chapter 5.1.1, Jedermann, Pötsch and Lloyd (2014) described that a transmission power of 1 mW, which is usually sufficient for a range of 10 to 100 m, dropped down to 0.5 m, when sensors were placed inside boxes of bananas. Another disadvantage of sensors placed inside boxes or packaging is that it requires additional work to place the sensors and to remove them after the consignment. One possible solution is to integrate sensor nodes into the container. However, this brings along the disadvantage that only the ambient conditions at either ceiling, floor, or walls of the container can be measured. Conditions inside boxes or pallets, or in the middle of the container cannot be determined in this way.

7.2 Communication of sensor system

The communication of wireless sensor networks can be divided into sensor layer communication and network layer communication. Sensor layer communication is basically the transmission of data between sensor nodes and gateway nodes, while communication on the network layer is the communication between gateway nodes and the remote server.

Sensor layer communication

For the communication on the sensor layer, different factors have to be taken into account. First of all, it is important to consider the frequency bandwidth. The ISM band is generally suitable for monitoring systems because it specifies a number of different frequency ranges that allows license-free operation. Jedermann, Pötsch, et al. (2014) recommends the use of the 433 MHz bandwidth over 2.4 GHz because lower frequencies are less attenuated. However, this frequency bandwidth is not available worldwide, but only in Europe, Africa, Middle East and Northern Asia (ITU, 2016). For a global system, such as a transport monitoring system, it is important that the system is permitted worldwide. Other smaller frequencies might be used but it needs to be ensured that a high enough data rate can be achieved in the selected frequency bandwidth.

Furthermore, the use of IEEE 802.15.4 standard was discussed in this report, which is specifically designed for low-cost and low-power applications, such as wireless sensor networks. Both ZigBee and 6LoWPAN are based on this standard. 6LoWPAN offers seamless interoperability with other IP devices, whereas ZigBee is more developed in terms of available software stacks (cf. chapter 3.2.3).

However, reliable communication also depends on other factors, such as the placement of sensor nodes (see chapter 7.1), the transmission power, and the content of the container. Therefore, it requires a compromise between different factors.

Network layer communication

One big challenge of today's monitoring systems is the real-time connectivity to remote servers as reported by the interviewees. This might be because of the utilization of mobile networks and the lack of coverage in remote areas or on the open ocean. However, even when satellite network communication is used instead, connectivity problems can occur. All satellite-based communication, whether it is GPS or a satellite data network, require line of sight between the antenna and a satellite. This also became evident when testing the GPS module for the proof of concept (see chapter 6.2). This issue can be particularly problematic on cargo ships where containers are stacked on top of each other. An idea is to utilize a local network on the transportation vehicle, e.g. the cargo ship could provide a WLAN, which itself is connected to a satellite network. Multiple access points on the ship could provide wireless access to this network for all containers. In this way, the gateway node of a container has to connect only to the local network and no line of sight to the satellite is necessary. This has multiple benefits, such as:

- The costs of the gateway node are lower because it only requires a cheaper communication module to connect to WLAN instead of a mobile network or satellite network module.
- The antenna of the gateway node does not require line of sight to the satellite.
- The local network can be utilized to alert the staff on the vehicle about the cargo conditions, even when no internet connection is available.

The downside is that the gateway node only functions with an existing network. This means that the transport vehicle has to provide this network, so that the data can be transmitted to the remote server. This is an approach that is probably used by Maersk (cf. Figure 11 in 3.3.5), however it is not entirely clear how their system works because technical information about the system is not disclosed publicly.

7.3 Power supply of sensor nodes

Sensor nodes can be powered in different ways. The use of self-powered nodes was mentioned in chapter 4.2, proposed by Chu et al. (2013). This seems like a very good alternative because no batteries need to be charged or replaced. However, it is questionable if the power transformed by the piezoelectric transducer is sufficient. It cannot be ensured that the harvested power is stable throughout the entire journey. Furthermore, the power consumption of the described device in the article required a power of only 225 µW, whereas the average power consumption of the sensor node described in chapter 5.1.1, statement 9, is with ca. 9 mW a lot higher. This suggests that the transmission power of the self-powered device is lower and might not be sufficient for a reliable communication.

The use of batteries requires good power management, such as utilizing sleep modes of the modules, so that the battery life can be extended as much as possible. If batteries are used, they have to be replaced or recharged, which incurs additional costs. Furthermore, the ambient temperature affects the battery life to a large extent, as tested by Ruiz-Garcia et al. (2008). These are all factors that have to be considered.

7.4 Costs and benefits

Whether a monitoring system is implemented and used in the industry depends to a great extent on the costs and benefits that it brings. Chapter 5.2 describes the cost-benefit analysis that is conducted in the scope of this project. The costs of the monitoring system are obviously mainly determined by the manufacturing costs of the devices. However, as shown in the analysis, there are other costs that can influence the total costs significantly. These are for instance network costs. If real-time connectivity is required on a transoceanic shipment, a regular mobile network cannot be utilized because there is no coverage on the sea. A satellite network can provide the necessary connection, but data costs are still very high today, which limits the amount of data that can be sent significantly.

Other, not so obvious costs are the costs of handling the devices. This includes attaching and detaching the nodes to and from the pallets and boxes, as well as possibly sending the nodes to the next deployment site. Consignments are one-way trips and the logistics of the devices have to be managed well so that these costs can be kept low. Maintenance costs, which can have a not so marginal impact as seen in chapter 5.2, include the replacement of devices and batteries. It could also include updating of firmware and other software so that the system is up-to-date, which is not considered in the cost-benefit analysis.

Regarding the benefits, the main financial benefit is most probably due to a higher product quality and lower spoilage, which can be achieved by optimization. The data gathered by the sensor nodes can bring several insights, e.g. whether the temperature control functions efficiently in keeping the ambient air at the required conditions or whether the cargo has been loaded and packed appropriately or cooling cannot reach certain locations inside the container. With the help of machine learning algorithms, the data could become even more valuable over time. The system could automatically compare data from similar consignments and thus provide information about good and bad practices.

Other benefits are that monitoring makes transportation processes more transparent, which can lead to a higher reputation of the carrier company. The increased transparency can also help to identify the responsible party when an incident happens, and the product quality becomes insufficient. This could potentially make expert assessments and negotiations redundant and effect cost savings. However, it is not clear to what extent this is possible and what kind of information the monitoring system would need to provide. In general, the monetary benefits are difficult to predict and most likely vary a lot case by case.

7.5 Logistics of equipment (material flow)

One challenge is to ensure the material flow of monitoring devices, i.e. when a monitored consignment is finished, the devices have to be moved back to the owner or to a place where they are needed next. This can be a difficult endeavor as this is an additional effort and cost. Scan Global Logistics reported in the interview that even managing the flow of containers is difficult today, especially when specialized containers are used that are not needed as often as regular containers. Consignments often go from place A to place B but when there is no consignment leaving from place B, it is difficult to manage the material flow. And shipping empty containers is a really expensive undertaking (cf. Appendix B), amounting to $700 to over $3000 for intercontinental shipping, depending on the location of the container (MoverDB.com, 2018).

As mentioned previously, one option to avoid this challenge is to make the costs of the devices so cheap that they can be disposed after one consignment. But is it really a better solution, even if the devices are cheap enough? Three points come to mind that may be detrimental to the idea. First of all, it would be an unsustainable solution as it would generate (electronic) waste, particularly when multiple devices are used in one shipment. Secondly, there would be a cost to dispose of the devices. And thirdly, even if the devices are only used for one consignment, they would have to be sent to the consignor in the first place anyway. Figure 21 shows the differences in material flow of a monitoring system with reusable devices compared to a system with not reusable devices. One possibility is that a third-party owner is involved in the process, which could be a freight forwarding company (solid arrows). This company would purchase the equipment and distribute it to the consignors, where the devices would be deployed inside the shipping container. This part of the material flow is the same for both reusable and not reusable monitoring equipment. The difference is in the end of the life cycle: reuse vs. disposal/recycling. If the infrastructure of the freight forwarding company is developed well and many companies are using monitoring devices, the freight forwarder could take care of the material flow. Another possibility is that the manufacturer and distributor of the equipment leases out the devices and takes care of the material flow after the equipment has been used (dashed arrows).

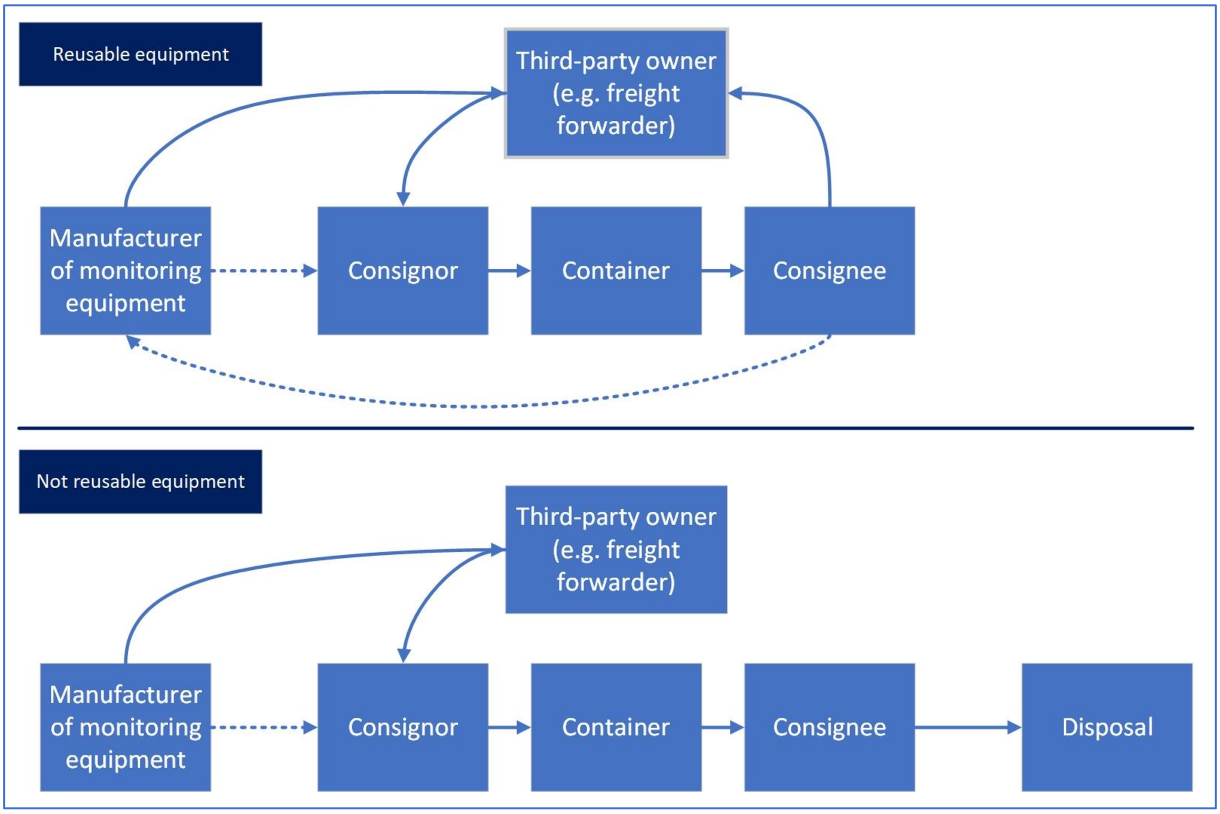

Figure 21 - Material flow of monitoring system

8 Conclusion

This report set out to analyze the requirements, costs and benefits of a wireless sensor system to monitor goods during transportation processes. Different aspects were set out to be analyzed, such as the deployment of the system, the technical communication, the power supply of sensor nodes, and the costs and benefits for different stakeholders. This was done by interviewing freight forwarding companies and reviewing scientific literature about proposed and tested monitoring systems. After collecting all data, relevant information has been extracted and structured into different categories. Then, requirements engineering has been conducted to transform the stakeholder needs and requirements into specific requirements for the system and system components. Furthermore, a cost-benefit analysis has been conducted to assess the costs and benefits that a monitoring system induces and to compare a more advanced system with systems currently used in the industry. This has been done by estimating the costs and benefits in a specific transportation scenario.

The following requirements for a transportation monitoring system have been concluded:

- The sensor node should be flexible in terms of sensor types that can be connected to it.
- The battery life of a sensor node should last for the duration of at least one consignment and the duty cycle should be variable so that the battery life can be extended.
- The wireless sensor network should be based on IEEE 802.15.4 at 2.4 GHz.
- The gateway node should be able to connect to the internet either via mobile or satellite network.
- The gateway node should determine the geographical location.
- The network should be able to handle 105 nodes or more.
- The transportation vehicle should provide a local network that the gateway node can connect to, in order to alert staff in case of problems.

The complete list of requirements is shown in Table 5 in chapter 5.1.2.

Costs and benefits of a system determine the adoption of it to a great extent. Chapter 5.2 described the process of a cost-benefit analysis that compared an advanced pallet- or item-level monitoring system with container-level monitoring as it is used in the industry today. Costs that have been determined comprise costs of hardware and software (incl. network costs), handling costs, maintenance costs, and other costs such as disposal costs. Benefits include an improved product quality, which leads to a reduction in spoilage, as well as improved transparency, and optimization potentials. The cost-benefit analysis shows that an advanced monitoring system can have significant benefits compared to no system or a container-level system. However, whether a monitoring system is economically viable, depends largely on the value of the transported products and how well the system helps to reduce losses. Aside from that, the costs should be kept low, which depends mainly on the hardware costs, handling costs, maintenance costs, and network costs.

All in all, based on the gathered information, it is difficult to develop a one-size-fits-all solution because there is a large variety of different products transported that all have different requirements, as well as different modes of transportation are used by different companies. A good approach is probably to decide on a specific niche, such as the transportation of fresh produce in intermodal containers and define specific requirements for this market. A specific solution can be developed and when the solution is validated and working successfully, it can be adapted to other markets.

9 List of references

Advanced Mobile Group. (2016). The Shocking Price of RFID Tags. Retrieved May 4, 2018, from http://www.advancedmobilegroup.com/blog/the-true-price-of-rfid-tags

Atmel Corporation. (2016). ATmega328/P Datasheet. Retrieved from http://ww1.microchip.com/downloads/en/DeviceDoc/Atmel-42735-8-bit-AVR-Microcontroller-ATmega328-328P_Datasheet.pdf

Bijwaard, D. J. A., van Kleunen, W. A. P., Havinga, P. J. M., Kleiboer, L., Bijl, M. J. J., Tsiftes, N., … Durvy, M. (2011). Industry: Using dynamic WSNs in smart logistics for fruits and pharmacy. In *Proceedings of the 9th ACM Conference on Embedded Networked Sensor Systems - SenSys '11* (p. 218). New York, New York, USA: ACM Press. https://doi.org/10.1145/2070942.2070965

Boardman, A. E., Greenberg, D. H., Vining, A. R., & Weimer, D. L. (2006). *Cost-Benefit Analysis - Concepts and Practice* (3rd ed.). New Jersey: Pearson Education, Inc.

Bukeviciute, L., Dierx, A., & Ilzkovitz, F. (2009). The functioning of the food supply chain and its effect on food prices in the European Union. European Commission. Retrieved from http://ec.europa.eu/economy_finance/publications/pages/publication15234_en.pdf

Castro, M., Jara, A. J., & Skarmeta, A. F. G. (2011). Analysis of the Future Internet of Things Capabilities for Continuous Temperature Monitoring of Blood Bags in Terrestrial Logistic Systems, 558–566. https://doi.org/10.1007/978-3-642-24082-9_68

Chen, M., & Chen, S. (2016). *RFID Technologies for Internet of Things*. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-47355-0

Chen, Y.-Y., Wang, Y.-J., & Jan, J.-K. (2014). A novel deployment of smart cold chain system using 2G-RFID-Sys. *Journal of Food Engineering*, *141*, 113–121. https://doi.org/10.1016/j.jfoodeng.2014.05.014

Chu, H., Wu, G., Chen, J., Fei, F., Mai, J. D., & Li, W. J. (2013). Design and simulation of self-powered radio frequency identification (RFID) tags for mobile temperature monitoring. *Science China Technological Sciences*, *56*(1), 1–7. https://doi.org/10.1007/s11431-012-5050-z

Churchill, J. (2016). Smart containers listen and talk. Retrieved February 9, 2018, from https://www.maersk.com/stories/smart-containers-listen-and-talk

Crainic, T. G., & Kim, K. H. (2007). Intermodal Transportation. In *Handbooks in Operations Research and Management Science* (Vol. 14, pp. 467–537). Elsevier. https://doi.org/10.1016/S0927-

0507(06)14008-6

de la Fuente Ruz, M., Higuera, A. G., Duro, J. A., Álvarez, A. A., & Sánchez, J. G.-E. (2007). SMART SENSOR IDENTIFIER (S2I) APPLICATION AND TRACKING OF SENSITIVE PRODUCTS. *IFAC Proceedings Volumes*, *40*(3), 233–239. https://doi.org/10.3182/20070523-3-ES-4908.00039

Decker, C., Berchtold, M., Weiss F. Chaves, L., Beigl, M., Roehr, D., Riedel, T., … Herzig, D. (n.d.). Cost-Benefit Model for Smart Items in the Supply Chain. In *The Internet of Things* (pp. 155–172). Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-78731-0_10

Dick, J., Hull, E., & Jackson, K. (2017). *Requirements Engineering*. Springer International Publishing. https://doi.org/10.1007/978-3-319-61073-3

Digi International Inc. (2009). XBee / XBee-PRO RF Modules Datasheet. Retrieved from https://www.sparkfun.com/datasheets/Wireless/Zigbee/XBee-Datasheet.pdf

Fedor, S., & Collier, M. (2007). On the Problem of Energy Efficiency of Multi-Hop vs One-Hop Routing in Wireless Sensor Networks. In *21st International Conference on Advanced Information Networking and Applications Workshops (AINAW'07)* (pp. 380–385). IEEE. https://doi.org/10.1109/AINAW.2007.272

G.-Escribano, J., de Dios, J. J., Pastor, J. M., & García, A. (2012). Improvement in the tracking of special loads by using a three-level RFID system. *International Journal of RF Technologies*, *3*(3), 181–199. https://doi.org/10.3233/RFT-2012-020

Ghosh, R. K. (2017). Low Power Communication Protocols: ZigBee, 6LoWPAN and ZigBee IP. In *Wireless Networking and Mobile Data Management* (pp. 147–177). Singapore: Springer Singapore. https://doi.org/10.1007/978-981-10-3941-6_6

Heidmann, N., Hellwege, N., Peters-Drolshagen, D., Paul, S., Dannies, A., & Lang, W. (2013). A low-power wireless UHF/LF sensor network with web-based remote supervision - Implementation in the intelligent container. In *2013 IEEE Sensors* (pp. 1–4). IEEE. https://doi.org/10.1109/ICSENS.2013.6688422

Heisselberg, S. (2018). phone interview with Regional Director Reefer Logistics, Kuehne+Nagel.

Hersent, O., Boswarthick, D., & Elloumi, O. (2012). *The internet of things : key applications and protocols*. John Wiley & Sons. Retrieved from http://library.books24x7.com.zorac.aub.aau.dk/toc.aspx?site=G45VZ&bookid=46260

Holdowsky, J., Mahto, M., Raynor, M. E., & Cotteleer, M. (2015). Inside the Internet of Things (IoT). *Deloitte Insights*, 54. Retrieved from https://www2.deloitte.com/insights/us/en/focus/internet-of-things/iot-primer-iot-technologies-applications.html

Igor. (2013). Arduino Power Consumption. Retrieved May 28, 2018, from https://www.gadgetmakersblog.com/arduino-power-consumption/

Institute for Microsensors -actuators and -systems (IMSAS). (n.d.). The intelligent container. Retrieved February 9, 2018, from http://www.intelligentcontainer.com/en/home.html

ITU. (2016). Radio Regulations. Retrieved from http://search.itu.int/history/HistoryDigitalCollectionDocLibrary/1.43.48.en.101.pdf

James, S. J., James, C., & Evans, J. A. (2006). Modelling of food transportation systems – a review. *International Journal of Refrigeration*, *29*(6), 947–957. https://doi.org/10.1016/J.IJREFRIG.2006.03.017

Jedermann, R., Nicometo, M., Uysal, I., & Lang, W. (2014). Reducing food losses by intelligent food logistics. *Philosophical Transactions. Series A, Mathematical, Physical, and Engineering Sciences*, *372*(2017). https://doi.org/10.1098/rsta.2013.0302

Jedermann, R., Pötsch, T., & Lloyd, C. (2014). Communication techniques and challenges for wireless food quality monitoring. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *372*(2017), 20130304–20130304. https://doi.org/10.1098/rsta.2013.0304

Jiménez-Ariza, T., Correa, E. C., Diezma, B., Silveira, A. C., Zócalo, P., Arranz, F. J., … Ruiz-Altisent, M. (2014). The Phase Space as a New Representation of the Dynamical Behaviour of Temperature and Enthalpy in a Reefer monitored with a Multidistributed Sensors Network. *Food and Bioprocess Technology*, *7*(6), 1793–1806. https://doi.org/10.1007/s11947-013-1191-8

K M, J. (2017). Wireless Sensor Network. *International Journal of Advanced Research in Computer Science and Software Engineering*, *7*(6), 588–596. https://doi.org/10.23956/ijarcsse/V7I6/0277

Kuehne+Nagel. (n.d.). Reefer Container: How does it work? Kuehne+Nagel.

Lascar Electronics. (2017). BS EN 12830:1999 - Declaration of Conformance. Retrieved from https://www.lascarelectronics.com/media/3107/bs-en-12830-1999_declaration-of-conformance_iss1_01-17.pdf

Li, C.-M., Nien, C.-C., Liao, J.-L., & Tseng, Y.-C. (2012). Development of wireless sensor module and network for temperature monitoring in cold chain logistics. In *2012 IEEE International Conference on Wireless Information Technology and Systems (ICWITS)* (pp. 1–4). IEEE. https://doi.org/10.1109/ICWITS.2012.6417745

Li, Y., Deng, R. H., & Bertino, E. (2013). RFID Security and Privacy. *Synthesis Lectures on Information Security, Privacy, and Trust*, *4*(3), 1–157. https://doi.org/10.2200/S00550ED1V01Y201311SPT007

Lu, L. X., & Swaminathan, J. M. (2015). Supply Chain Management. In *International Encyclopedia of the Social & Behavioral Sciences* (pp. 709–713). Elsevier. https://doi.org/10.1016/B978-0-08-097086-8.73032-7

Luo, H., Zhu, M., Ye, S., Hou, H., Chen, Y., & Bulysheva, L. (2016). An intelligent tracking system based on internet of things for the cold chain. *Internet Research*, *26*(2), 435–445. https://doi.org/10.1108/IntR-11-2014-0294

Minoli, D. (2013). *Building the Internet of Things with IPv6 and MIPv6 : the Evolving World of M2M Communications.* Wiley. Retrieved from http://library.books24x7.com.zorac.aub.aau.dk/toc.aspx?site=G45VZ&bookid=56259

Miovic, A. (2018). MOST. Mobsentech.

MoverDB.com. (2018). 2018 International Conatiner Shipping Rates & Costs. Retrieved May 22, 2018, from https://moverdb.com/container-shipping/

Nascimento Nunes, M. C. do, Nicometo, M., Emond, J. P., Melis, R. B., & Uysal, I. (2014). Improvement in fresh fruit and vegetable logistics quality: berry logistics field studies. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *372*(2017), 20130307–20130307. https://doi.org/10.1098/rsta.2013.0307

Nechifor, S., Petrescu, A., Damian, D., Puiu, D., & Tarnauca, B. (2014). Predictive analytics based on CEP for logistic of sensitive goods. In *2014 International Conference on Optimization of Electrical and Electronic Equipment (OPTIM)* (pp. 817–822). IEEE. https://doi.org/10.1109/OPTIM.2014.6850965

Piramuthu, S., & Zhou, W. (2016). *RFID and Sensor Network Automation in the Food Industry : Ensuring Quality and Safety through Supply Chain Visibility.* Wiley.

PowerStream Technology. (2017). Discharge tests of Alkaline AA batteries. Retrieved May 15, 2018, from https://www.powerstream.com/AA-tests.htm

Pursche, F. (2016). Container 4.0: Smart transport on the high seas - Bosch ConnectedWorld Blog. Retrieved April 17, 2018, from https://blog.bosch-si.com/industry40/container-4-0-smart-transport-high-seas/

reed.co.uk. (2017). Transport & Logistics Average Salaries in UK. Retrieved May 25, 2018, from https://www.reed.co.uk/average-salary/transport-logistics

RightBattery.com. (2013). 1.5V AAA Duracell Alkaline Battery Tests. Retrieved May 18, 2018, from https://rightbattery.com/283-1-5v-aaa-duracell-alkaline-battery-tests/

Rogers, Y., Sharp, H., & Preece, J. (2011). *Interaction design : beyond human-computer interaction*. Wiley.

Ruiz-Garcia, L., Barreiro, P., & Robla, J. I. (2008). Performance of ZigBee-Based wireless sensor nodes for real-time monitoring of fruit logistics. *Journal of Food Engineering*, *87*(3), 405–415. https://doi.org/10.1016/j.jfoodeng.2007.12.033

Santa, J., Zamora-Izquierdo, M. A., Jara, A. J., & Gómez-Skarmeta, A. F. (2012). Telematic platform for integral management of agricultural/perishable goods in terrestrial logistics. *Computers and Electronics in Agriculture*, *80*, 31–40. https://doi.org/10.1016/j.compag.2011.10.010

Sarmiento M, D., Zhibo Pang, Sanchez, M. F., Qiang Chen, Tenhunen, H., & Li-Rong Zheng. (2010). Mobile wireless sensor system for tracking and environmental supervision. In *2010 IEEE International Symposium on Industrial Electronics* (pp. 470–477). IEEE. https://doi.org/10.1109/ISIE.2010.5637855

Seco, T., Bermudez, J., Paniagua, J., & Castellanos, J. A. (2011). Dynamic and Heterogeneous Wireless Sensor Networks for Virtual Instrumentation Services: Application to Perishable Goods Surveillance. In *2011 IEEE Eighth International Conference on Mobile Ad-Hoc and Sensor Systems* (pp. 849–854). IEEE. https://doi.org/10.1109/MASS.2011.99

Sen, D., Sen, P., & Das, A. M. (2009). *RFID for Energy & Utility Industries*. PennWell. Retrieved from https://books.google.dk/books/about/RFID_for_Energy_Utility_Industries.html?id=zSZHbngCGO0C&redir_esc=y

Shelby, Z., & Bormann, C. (2009). *6LoWPAN : the wireless embedded internet*. John Wiley & Sons. Retrieved from http://library.books24x7.com.zorac.aub.aau.dk/toc.aspx?site=G45VZ&bookid=36453

Struthers, C. (2016). The Cost of Recycling E-Waste is becoming a Problem. Retrieved May 23, 2018, from https://sites.psu.edu/cstruthersblog/2016/04/27/the-cost-of-recycling-e-waste-is-becoming-a-problem/

Sun, A., & Goldbach, G. (2013). How a Flexible Supply Chain Delivers Value. Retrieved May 26, 2018, from http://www.industryweek.com/procurement/how-flexible-supply-chain-delivers-value

Tennina, S., Koubâa, A., Daidone, R., Alves, M., Jurčík, P., Severino, R., … Tovar, E. (2013). *IEEE 802.15.4 and ZigBee as Enabling Technologies for Low-Power Wireless Systems with Quality-of-Service*

Constraints. Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-37368-8

Traub, K. (2016). EPC Memory vs. User Memory. *RFID Journal*. Retrieved from http://www.rfidjournal.com/articles/view?15156

Tuczynski. (2009). Satellite Internet At Sea: Hardware, Airtime, and Pricing. Retrieved May 23, 2018, from http://www.globalmarinenet.com/satellite-internet-at-sea-hardware-airtime-and-pricing/

Wang, Y., Yi, J., Zhu, X., Luo, J., & Ji, B. (2015). Developing an Ontology-Based Cold Chain Logistics Monitoring and Decision System. *Journal of Sensors*, *2015*, 1–8. https://doi.org/10.1155/2015/231706

Weis, S. A. (2007). *RFID (Radio Frequency Identification): Principles and Applications*. Retrieved from https://www.rfid-off.com/uploads/4/5/1/2/45128343/rfid-article_mit_usa.pdf

Wilson, J. S. (2004). *Sensor Technology Handbook*. Elsevier Inc.

Xiao, X., Fu, Z., Zhang, Y., Peng, Z., & Zhang, X. (2017). SMS-CQ: A Quality and Safety Traceability System for Aquatic Products in Cold-Chain Integrated WSN and QR Code. *Journal of Food Process Engineering*, *40*(1), e12303. https://doi.org/10.1111/jfpe.12303

Zhang, H., & Yang, S. (2017). Research on Application of WSN in Cold Chain Logistics' Warehousing and Transportation (pp. 589–598). https://doi.org/10.1007/978-981-10-3530-2_74

Zhang, Z., Chen, Q., Bergarp, T., Norman, P., Wikstrom, M., Yan, X., & Zheng, L.-R. (2009). Wireless sensor networks for logistics and retail. In *2009 Sixth International Conference on Networked Sensing Systems (INSS)* (pp. 1–4). IEEE. https://doi.org/10.1109/INSS.2009.5409943

Appendices

Appendix A

Literature search protocol & search results

This chapter shows the search protocol used for the literature review, as well as the resulting references.

Search Protocol

1. Define your research subject and describe the specific focus of the performed search:

Wireless sensor network for monitoring the transport of perishable goods

2. List the aspects that your subject contains and the search terms for each of the aspects:

Aspect 1 (Wireless sensor network)	Aspect 2 (monitoring)	Aspect 3 (transport)	Aspect 4 (perishable, fragile)	Aspect 5 (goods)
Wireless sensors WSN Internet of Things IoT	Monitoring Tracking	Transportation Logistics	Perishable Spoilable Short-lived Fragile Brittle	Goods Food Products Items

3. Selection of relevant sources:

Source (databases, search engines, sources hand searched, persons/organizations contacted...)	Provider (which provider you accessed the source through)	Reason for selection of source (subject coverage, accessibility, key source…)
Engineering Village		Covers engineering area, uses Compendex, one of the biggest engineering bibliography databases

4. Define your inclusion and exclusion criteria (both formal characteristics (e.g. study design, language, year) and content-related considerations)

Inclusion criteria	peer-reviewed articles
Exclusion criteria	

5. The performed searches

Source	Search query (paste your exact query from the searched source to includes field codes in the search query)	Limitations (year, publication type, peer reviewed,…)
Engineering Village	("wireless sensor" OR "wireless sensors" OR WSN OR IoT OR "Internet of Things") AND (monitor* OR track*) AND (transport* OR logistic*) AND (perish* OR spoil* OR short-lived OR fragile OR brittle) AND (good* OR food* OR product* OR item*)	

6. Search results

Source	Number of results and number of relevant results in parentheses	Date of performed search
Engineering Village	30 (20)	08.03.2018

7. Date of finalization of search protocol, persons involved and their organizational affiliation

Performed by Stefan Breisch, ICTE 4th semester, Aalborg University, 8th of March 2018

Search results

1. Research on key techniques for monitoring system of agricultural products transportation environment based on internet of things

Cao, Jianhua (Institute of Information and Technology, Chinese Academy of Tropical Agricultural Sciences, Danzhou 571737, China); Wang, Lingling; Luo, Hongxia **Source:** *Advanced Materials Research*, v 588-589, p 1086-1090, 2012, *Advances in Mechanics Engineering*
Database: Compendex
Compilation and indexing terms, Copyright 2018 Elsevier Inc.
Data Provider: Engineering Village

2. Analysis of the future internet of things capabilities for continuous temperature monitoring of blood bags in terrestrial logistic systems

Castro, Miguel (Department of Information and Communication Engineering, University of Murcia, Murcia, Spain); Jara, Antonio J.; Skarmeta, Antonio F. G. **Source:** *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, v 6935 LNCS, p 558-566, 2011, *Convergence and Hybrid Information Technology - 5th International Conference, ICHIT 2011, Proceedings*
Database: Compendex

Compilation and indexing terms, Copyright 2018 Elsevier Inc.
Data Provider: Engineering Village

3. Dynamic and heterogeneous wireless sensor networks for virtual instrumentation services: Application to perishable goods surveillance

Seco, T. (Grupo de Investigación Aplicada (GIA-MDPI), Instituto Tecnológico de Aragón, Zaragoza, Spain); Bermúdez, J.; Paniagua, J.; Castellanos, J.A. **Source:** *Proceedings - 8th IEEE International Conference on Mobile Ad-hoc and Sensor Systems, MASS 2011*, p 849-854, 2011, *Proceedings - 8th IEEE International Conference on Mobile Ad-hoc and Sensor Systems, MASS 2011*
Database: Compendex
Compilation and indexing terms, Copyright 2018 Elsevier Inc.
Data Provider: Engineering Village

4. Wireless sensor networks for logistics and retail

Zhang, Zhi (Ipack VINN Excellence Center, Royal Institute of Technology, Stockholm, Sweden); Chen, Qiang; Bergarp, Tobia; Norman, Per; Wikström, Magnus; Yan, Xiaolang; Zheng, Li-Rong **Source:** *INSS2009 - 6th International Conference on Networked Sensing Systems*, p 98-101, 2009, *INSS2009 - 6th International Conference on Networked Sensing Systems*
Database: Compendex
Compilation and indexing terms, Copyright 2018 Elsevier Inc.
Data Provider: Engineering Village

5. Toward an intelligent solution for perishable food cold chain management

Lu, Sichao (School of Traffic and Transportation, Beijing Jiaotong University, China); Wang, Xifu **Source:** *Proceedings of the IEEE International Conference on Software Engineering and Service Sciences, ICSESS*, p 852-856, March 20, 2017, *ICSESS 2016 - Proceedings of 2016 IEEE 7th International Conference on Software Engineering and Service Science*
Database: Compendex
Compilation and indexing terms, Copyright 2018 Elsevier Inc.
Data Provider: Engineering Village

6. A low-power wireless UHF/LF sensor network with web-based remote supervision - Implementation in the intelligent container

Heidmann, Nils (Institute of Electrodynamics and Microelectronics, University of Bremen, Germany); Hellwege, Nico; Peters-Drolshagen, Dagmar; Paul, Steffen; Dannies, Alexander; Lang, Walter **Source:** *Proceedings of IEEE Sensors*, 2013, *IEEE SENSORS 2013 - Proceedings*
Database: Compendex
Compilation and indexing terms, Copyright 2018 Elsevier Inc.
Data Provider: Engineering Village

7. Research on application of WSN in cold chain logistics' warehousing and transportation

Zhang, Hanyue (Tianjin University of Science & Technology, Tianjin, China); Yang, Shijuan **Source:** *Lecture Notes in Electrical Engineering*, v 417, p 589-598, 2017
Database: Compendex
Compilation and indexing terms, Copyright 2018 Elsevier Inc.
Data Provider: Engineering Village

8. A novel deployment of smart cold chain system using 2G-RFID-Sys

Chen, Yu-Yi (Department of Management Information System, National Chung Hsing University, 250 Kuo Kuang Road, 402 Taichung, Taiwan); Wang, Yao-Jen; Jan, Jinn-Ke **Source:** *Journal of Food Engineering*, v 141, p 113-121, November

2014
Database: Compendex

Data Provider: Engineering Village

9. Design and simulation of self-powered radio frequency identification (RFID) tags for mobile temperature monitoring

Chu, Hequn (Department of Physics, Faculty of Science, Kunming University of Science and Technology, Kunming 650500, China); Wu, Guangmin; Chen, Jianming; Fei, Fei; Mai, John D.; Li, Wen J. **Source:** *Science China Technological Sciences*, v 56, n 1, p 1-7, January 2013, *Special Topic on NanoScience and Technology*
Database: Compendex

Data Provider: Engineering Village

10. SMS-CQ: A Quality and Safety Traceability System for Aquatic Products in Cold-Chain Integrated WSN and QR Code

Xiao, Xinqing (China Agricultural University, Beijing, China); Fu, Zetian; Zhang, Yongjun; Peng, Zhaohui; Zhang, Xiaoshuan **Source:** *Journal of Food Process Engineering*, v 40, n 1, February 1, 2017
Database: Compendex

Data Provider: Engineering Village

11. Development of wireless sensor module and network for temperature monitoring in cold chain logistics

Li, Chen-Ming (Industrial Technology Research Institute (ITRI), Chutung, Hsinchu, 310, Taiwan); Nien, Chin-Chung; Liao, Jia-Liang; Tseng, Yu-Chee **Source:** *2012 IEEE International Conference on Wireless Information Technology and Systems, ICWITS 2012*, 2012, *2012 IEEE International Conference on Wireless Information Technology and Systems, ICWITS 2012*
Database: Compendex

Data Provider: Engineering Village

12. Mobile wireless sensor system for tracking and environmental supervision

David, Sarmiento M. (IPack Vinn Excellence Center, School of Information and Communication Technology KTH-Royal, Institute of Technology, Kista-Stockholm, Sweden); Pang, Zhibo; Sanchez, Mario F.; Chen, Qiang; Tenhunen, Hannu; Zheng, Li-Rong **Source:** *IEEE International Symposium on Industrial Electronics*, p 470-477, 2010, *ISIE 2010 - 2010 IEEE International Symposium on Industrial Electronics*
Database: Compendex

Data Provider: Engineering Village

13. Mitigating risks of perishable products in the cyber-physical systems based on the extended MRP model

Bogataj, David (Department of Management and Engineering, University of Padua, Italy); Bogataj, Marija; Hudoklin, Domen **Source:** *International Journal of Production Economics*, v 193, p 51-62, November 2017
Database: Compendex

Data Provider: Engineering Village

14. Industry: Using dynamic WSNs in smart logistics for fruits and pharmacy

Bijwaard, Dennis J. A. (Ambient Systems, Colosseum 15d, 7521PV Enschede, Netherlands); Van Kleunen, Wouter A. P.; Havinga, Paul J. M.; Kleiboer, Leon; Bijl, Mark J. J. **Source:** *SenSys 2011 - Proceedings of the 9th ACM Conference on Embedded Networked Sensor Systems*, p 218-231, 2011, *SenSys 2011 - Proceedings of the 9th ACM Conference on Embedded Networked Sensor Systems*
Database: Compendex
Compilation and indexing terms, Copyright 2018 Elsevier Inc.
Data Provider: Engineering Village

15. Performance of ZigBee-Based wireless sensor nodes for real-time monitoring of fruit logistics

Ruiz-Garcia, L. (Laboratorio de Propiedades Físicas, Tecnologías Avanzadas en Agroalimentación, ETSI Agrónomos, Avda. Complutense s/n, 28040 Madrid, Spain); Barreiro, P.; Robla, J.I. **Source:** *Journal of Food Engineering*, v 87, n 3, p 405-415, August 2008
Database: Compendex
Compilation and indexing terms, Copyright 2018 Elsevier Inc.
Data Provider: Engineering Village

16. Cost-benefit model for smart items in the supply chain

Decker, Christian (Telecooperation Office (TecO), University of Karlsruhe); Berchtold, Martin; Chaves, Leonardo Weiss F.; Beigl, Michael; Roehr, Daniel; Riedel, Till; Beuster, Monty; Herzog, Thomas; Herzig, Daniel **Source:** *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, v 4952 LNCS, p 155-172, 2008, *The Internet of Things - First International Conference, IOT 2008, Proceedings*
Database: Compendex
Compilation and indexing terms, Copyright 2018 Elsevier Inc.
Data Provider: Engineering Village

17. Maximizing value of perishable products by implementing RFID technology

Askin, Ronald G. (Arizona State University, Tempe AZ 85287-8809, United States); Khodadadegan, Yasaman; Haghnevis, Moeed **Source:** *IIE Annual Conference and Expo 2010 Proceedings*, 2010, *IIE Annual Conference and Expo 2010 Proceedings*
Database: Compendex
Compilation and indexing terms, Copyright 2018 Elsevier Inc.
Data Provider: Engineering Village

18. Telematic platform for integral management of agricultural/perishable goods in terrestrial logistics

Santa, José (Department of Information and Communication Engineering, Computer Science Faulty, University of Murcia, 30100 Murcia, Spain); Zamora-Izquierdo, Miguel A.; Jara, Antonio J.; Gómez-Skarmeta, Antonio F. **Source:** *Computers and Electronics in Agriculture*, v 80, p 31-40, January 2012
Database: Compendex
Compilation and indexing terms, Copyright 2018 Elsevier Inc.
Data Provider: Engineering Village

19. Improvement in the tracking of special loads by using a three-level RFID system

Ga-Escribano, Javier (University of Castilla-La Mancha, Ciudad Real, Spain); De Dios, Juan J.; Pastor, José Manuel; García, Andrés **Source:** *International Journal of RF Technologies: Research and Applications*, v 3, n 3, p 181-199, 2012
Database: Compendex
Compilation and indexing terms, Copyright 2018 Elsevier Inc.
Data Provider: Engineering Village

20. Developing an ontology-based cold chain logistics monitoring and decision system

Wang, Yujun (Department of Mechanical Engineering, East China University of Science and Technology, Shanghai, China); Yi, Jianjun; Zhu, Xiaomin; Luo, Jinlong; Ji, Baiyang **Source:** *Journal of Sensors*, v 2015, 2015
Database: Compendex
Compilation and indexing terms, Copyright 2018 Elsevier Inc.
Data Provider: Engineering Village

21. Smart sensor identifier (s2I) application and tracking of sensitive products

De La Fuente Ruzz, M. (Universidad Jaén, Spain); García Higuera, A.; Abril Duro, J.; Abarca Álvarez, A.; Escribano Sánchez, J.G. **Source:** *IFAC Proceedings Volumes (IFAC-PapersOnline)*, v 8, n PART 1, p 233-240, 2007, *IFAC International Workshop on Intelligent Manufacturing Systems, IMS'07 - Proceedings*
Database: Compendex
Compilation and indexing terms, Copyright 2018 Elsevier Inc.
Data Provider: Engineering Village

22. The Phase Space as a New Representation of the Dynamical Behaviour of Temperature and Enthalpy in a Reefer monitored with a Multidistributed Sensors Network

Jiménez-Ariza, T. (Laboratorio de Propiedades Físicas y Tecnologías Avanzadas en Agroalimentación, Departamento de Ingeniería Rural, ETSI Agrónomos, Universidad Politécnica de Madrid-CEI Moncloa, Av. Complutense s/n, Ciudad Universitaria, 28040 Madrid, Spain); Correa, E.C.; Diezma, B.; Silveira, A.C.; Zócalo, P.; Arranz, F.J.; Moya-González, A.; Garrido-Izard, M.; Barreiro, P.; Ruiz-Altisent, M. **Source:** *Food and Bioprocess Technology*, v 7, n 6, p 1793-1806, 2014
Database: Compendex
Compilation and indexing terms, Copyright 2018 Elsevier Inc.
Data Provider: Engineering Village

23. An experimental investigation of applying Mica2 Motes in pavement condition monitoring

Pei, Jin-Song (School of Civil Engineering and Environmental Science, University of Oklahoma, Norman, OK 73019-1024, United States); Ivey, Richard A.; Lin, Hungjr; Landrum, Aaron R.; Sandburg, Colby J.; Ferzli, Nadim A.; King, Timothy; Zaman, Musharraf M.; Refai, Hazem H.; Mai, Eric C. **Source:** *Journal of Intelligent Material Systems and Structures*, v 20, n 1, p 63-85, January 2009
Database: Compendex
Compilation and indexing terms, Copyright 2018 Elsevier Inc.
Data Provider: Engineering Village

24. Context-aware inference model for cold-chain logistics monitoring

Engel, Ventje Jeremias Lewi (School of Electrical Engineering and Informatics, Institut Teknologi Bandung, Bandung, Indonesia); Supangkat, Suhono Harso **Source:** *Proceedings - 2014 International Conference on ICT for Smart Society: "Smart System Platform Development for City and Society, GoeSmart 2014", ICISS 2014*, p 192-196, January 16, 2014
Database: Compendex
Compilation and indexing terms, Copyright 2018 Elsevier Inc.
Data Provider: Engineering Village

25. Predictive analytics based on CEP for logistic of sensitive goods

Nechifor, Septimiu (Siemens Corporate Technology Romania, Romania); Petrescu, Anca; Damian, Dragos¸; Puiu, Dan; Târnaucaˇ, Bogdan **Source:** *2014 International Conference on Optimization of Electrical and Electronic Equipment, OPTIM 2014*, p 817-822, 2014, *2014 International Conference on Optimization of Electrical and Electronic Equipment, OPTIM 2014*
Database: Compendex

Compilation and indexing terms, Copyright 2018 Elsevier Inc.
Data Provider: Engineering Village

26. Cold supply chain logistics: System optimization for real-time rerouting transportation solutions

Mejjaouli, Sobhi (Assistant Professor of Industrial Engineering, Department of Industrial Engineering, Alfaisal University, Riyadh, Saudi Arabia); Babiceanu, Radu F. **Source:** *Computers in Industry*, v 95, p 68-80, February 2018
Database: Compendex
Compilation and indexing terms, Copyright 2018 Elsevier Inc.
Data Provider: Engineering Village

27. Smart sensing system integration: From silicon to plastic foil

Briand, Danick (Ecole Polytechnique Federale de Lausanne (EPFL), Institute of Microengineering (IMT), Sensors, Actuators and Microsystems Laboratory (SAMLAB), Neuchatel, Switzerland); Courbat, Jerome; De Rooij, Nico F. **Source:** *Smart Systems Integration 2010 - 4th European Conference and Exhibition on Integration Issues of Miniaturized Systems - MEMS, MOEMS, ICs and Electronic Components*, 2010, *Smart Systems Integration 2010 - 4th European Conference and Exhibition on Integration Issues of Miniaturized Systems - MEMS, MOEMS, ICs and Electronic Components*
Database: Compendex
Compilation and indexing terms, Copyright 2018 Elsevier Inc.
Data Provider: Engineering Village

28. Integrated monitoring and control system for production, supply chain and logistics operations

Mejjaouli, Sobhi (Department of Systems Engineering, University or Arkansas at Little Rock, Little Rock; AR, United States); Babiceanu, Radu F. **Source:** *FAIM 2014 - Proceedings of the 24th International Conference on Flexible Automation and Intelligent Manufacturing: Capturing Competitive Advantage via Advanced Manufacturing and Enterprise Transformation*, p 29-36, 2014, *FAIM 2014 - Proceedings of the 24th International Conference on Flexible Automation and Intelligent Manufacturing: Capturing Competitive Advantage via Advanced Manufacturing and Enterprise Transformation*
Database: Compendex
Compilation and indexing terms, Copyright 2018 Elsevier Inc.
Data Provider: Engineering Village

29. Cold chain management in meat storage, distribution and retail: A review

Nastasijević, I. (Institute of Meat Hygiene and Technology, Kacanskog 13, Belgrade, Serbia); Lakićević, B.; Petrović, Z. **Source:** *IOP Conference Series: Earth and Environmental Science*, v 85, n 1, September 26, 2017, *59th International Meat Industry Conference, MEATCON 2017*
Database: Compendex
Compilation and indexing terms, Copyright 2018 Elsevier Inc.
Data Provider: Engineering Village

30. Reducing food losses by intelligent food logistics

Jedermann, Reiner (Institute for Microsensors, Actuators and Systems (IMSAS), University of Bremen, Bremen, Germany); Nicometo, Mike; Uysal, Ismail; Lang, Walter **Source:** *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, v 372, n 2017, June 13, 2014
Database: Compendex
Compilation and indexing terms, Copyright 2018 Elsevier Inc.
Data Provider: Engineering Village

Appendix B

Interviews

This chapter shows summaries of the conducted interviews.

Interview with Kuehne+Nagel

- Date: 12.03.2018
- Type of interview: phone interview, semi-structured
- Interviewee: Svend Heisselberg, Regional Director Reefer Logistics
- Department: Reefer Logistics, Kuehne+Nagel A/S

Questions regarding transportation

How are the goods packed into the container?

On the producer's site, the fresh goods are packed into transport boxes, which are then loaded into the container. Depending on the type of product, different type of boxes are used, e.g. cardboard boxes for bananas.

What happens to the goods when the means of transport changes?

It is most often transported intermodally, meaning the entire container changes means of transportation and no unloading and reloading processes are necessary. On the ship, the reefer container is connected to the power supply of the ship. During loading and unloading, there is usually no power provided, and sometimes not even on the road as temperature changes very slowly. However, this depends on the type of product and on ambient temperature and humidity. It is a much bigger issue for pharmaceuticals because the transport conditions are much stricter.

Which part of the transport route affects the food quality the most?

On the long part of the journey, usually the sea transportation because temperature and time are the most important aspects.

What are the main reasons for food spoilage?

Food spoilage during transportation mostly occurs because of improper packing and loading of the goods, as well as bad conditions of the food before transportation. Technical reasons, such as failure of the refrigeration unit, are not so much a problem.

Questions regarding monitoring system

Does your company uses a monitoring system?

Yes, we use a system called *MOST* from the company *Mobsentech*.

What parameters can be monitored with the monitoring system that your company is using?

It is possible to monitor all kinds of parameters, depending on what the customer needs and what he wants to pay, e.g. temperature, humidity, air composition, ethylene, etc. However, monitoring temperature is the most important.

How many sensors are used per container?

Only one.

Where are the sensor located?

It is located close to the air inlet, measuring the supply air.

How are the sensors powered?

The sensor are battery-powered. The entire module is fairly cheap so that it will be thrown out after the journey. But there are also system, where the sensor is integrated into the container and uses the same power supply as the cooling unit.

Are there still problems despite the system or because of the system?

Sometimes, there is no connection and you don't have real-time monitoring. But parameters are still measured and stored and transmitted to the server later on.

Questions regarding stakeholders

Who are the stakeholders directly involved in a transportation process?

Consignee (receiver of goods), shipping line, freight forwarder (e.g. K+N) and producer

Who is responsible for the goods? Who is liable when the goods become unsaleable during transport?

That depends on the reason for the damage of the goods If the reason is that the temperature is not kept within range, then it is fault of the shipping line and the consignee gets compensated by an insurance company. If the reason is that the goods were already in insufficient condition or goods were packed improperly, then the claim can be denied. It is up to the insurance company to assess the situation.

Who is interested in monitoring the goods?

The shipping line is interested in monitoring the goods because they are liable if there are temperature failures, etc. The consignee is interested as well because in case there are temperature failures, they can make a claim. This results in two separate monitoring systems, one proprietary one integrated into the container and only used be the shipping company (they generally don't disclose the information, unless there is a claim) and one by the consignee, which is usually just put into the container. Some shipping lines offer their customers access to the monitoring data via an online platform.

Additional information (added 19.04.2018 by email)

How is it determined who is liable for damage of the goods?

When there is a cargo claim, both the shipping line and consignee will arrange inspection by their own independent cargo surveyors. These surveyors act 100% independent and provide a written report of the claim, including a statement why the cargo is damaged (e.g. temperature issues, insufficient packing, etc.). These reports are sent to the respective insurance companies for further claim settlement.

Interview with Scan Global Logistics

- Date: 06.04.2018
- Type of interview: personal interview (face-to-face), semi-structured
- Interviewee: Kuno Lange Jensen, IT Director
- Department: Corporate IT, Scan Global Logistics A/S

General information

- We are not transporting by ourselves but hiring the carriers/shipping lines to do the transportation mainly.

- We are only owning trailers.

Questions regarding monitoring system

Do you have a monitoring system in place?

Environment monitoring (temperature, etc.), if done at all, is done by the carrier who sends the data back to us. We are doing the forwarding. You can say we are only organizing the transportation. So, if you would be the customer and you want temperature control, we would say to the carrier that we need to have a temperature-controlled environment and you need to send the data to us. Then the customer can access the data either through our system or access it in their system through EDI (electronic data interchange).

Can the customer access the data in real-time or is it reported later on in the process?

Usually, it is reported. Let's suppose we have air freight in frozen containers and make a booking at an airline and then we use a network over which the airline sends all the information back regarding this shipment. And most often this data comes nearly right away. But sometimes it doesn't, or it doesn't come at all. And this is actually one of the major challenges in the industry because we don't control the logistics chain because we have hired companies to do that for us. So, we are dependent on receiving the data back. But I would not say it is real-time.

However, sometimes when we send cars for aid & relief to Africa, we ourselves put in a GPS module, so we know all the time where they are. But it needs to have some certain kind of value in order to be beneficial. It depends always on how much money you want to put in.

Do you know why the data from the carriers sometimes comes delayed or not at all?

To be honest, no.

But the problem is if we should put in devices for monitoring our shipments, then we also need to have the devices back. So, there is also a flow that has to be managed. I think if the prices would be very low, we would just put in a device but at the moment the prices are too high.

We do use some RFID tags but mainly for warehousing. But this is only for track & trace, meaning you can see when the goods have arrived at the warehouse and left the warehouse.

Do you also use RFID chips during the transportation process?

Well, these chips are usually only scanned on delivery and departure. If during transportation a box is taken away, we cannot track where it is.

Are these RFID tags attached on a item level, meaning are they attached to every product?

It could be item-level. But again, there is this price issue. So usually, it is more on a pallet level. So, on a pallet you have linked for instance 1000 items. But they are usually wrapped together. So, this needs to be destroyed if single products are lost.

Regarding temperature monitoring, is this usually done on a pallet level or rather on the container level?

Well, this depends on the product, its value and how important it is. But even with pharmaceuticals, it is often not temperature-controlled. In the warehouse, it is of course stored in a freezer. But when it is shipped by airplane, it is usually just put into a box with ice. And it needs to be ensured that it is re-iced on the way. This is generally done by the airline, which has to confirm that it has been done.

How is it then secured that the cold chain is never broken?

Everything needs to be documented. However, as this is a manual process, this could of course go wrong. So, a chip monitoring everything would be perfect here.

Is there generally a big problem of perishable goods such as food or pharmaceuticals being wasted during transported because of that?

Not to my knowledge. But I don't really know if there is a lot of waste.

Especially with pharmaceuticals, it is more securing that all this processes are well documented because our customers need to live up to some legal standards. But also with dangerous goods, such as explosives or even batteries, a lot of guidelines have to be followed.

Regarding dangerous goods, is there some kind of monitoring of certain parameters be done?

Not really. But I think, it will come.

However, in general I think there are 3 main challenges. One is the price. It must be cost-efficient. Second is connectivity. When the goods are somewhere out on the sea and there is some kind of monitoring, it also needs to be reported back. And third is the material flow. Somehow, these items need to find there way back to us. And actually, also when you get all this data, and you see there is something going wrong, you also need to act on it immediately and fix the problem.

Regarding the material flow, if these devices are integrated into the container, wouldn't that solve the issue?

Then, the containers need to find their way back. This is actually also a problem today. However, there are mostly used standard containers, which can be used for a lot of different things. But if you have special containers with integrated devices, they will probably only be used for certain goods, making this process more difficult. And it is really expensive to send back an empty container.

Coming back to the data you are getting from the carriers about environmental parameters such as temperature, what is the real benefit for the customer?

Mainly it is the legal aspect, so the customer has to document that there is no breach in the cold chain for instance.

Therefore, it is usually not required for them to receive the data in real-time. Again, real-time monitoring is usually done seldom. I think it is really just one customer for whom we are doing real-time temperature monitoring. You also need to think about, if you see that a certain temperature-controlled box is broken in real-time, then you need to act on it. And maybe you can't act on it. Then it is only important to know about the issues, and that is not necessary in real-time.

I think if you want real-time monitoring to work, you actually need the ship to function as the access point. In this industry, there are a lot of good and bad IT products. The challenge I think is also to standardize it.

Additional information (added 25.04.2018 by email)

What are today's cost of a monitoring system?

The annual license fee of a system is approx. $1000 per user. However, this does not include costs related to the implementation of the system, such as customization, operational costs, implementation costs, etc.

Interview with Freja

- Date: 12.04.2018
- Type of interview: phone interview, semi-structured
- Interviewee: Kenneth Sandgaard, Business Development Manager
- Department: Business Development, Freja Transport & Logistics A/S

General information

- Specialized in transport of pharmaceuticals
- 90% of revenue comes from road transportation

Questions regarding monitoring system

What parameters are being monitored with your monitoring system?

That depends very much on the specific case of the customer. But if we take pharmaceuticals for example, it is often temperature and humidity. Furthermore, the location is also an important parameter, so we can see if the truck is on the correct route and also to see if the truck is on time and to estimate when it will arrive. But we can for example also see if the doors of the truck have been opened between the departure and arrival and where that was. Basically, it increases the transparency of several actions taken during the transport of the goods.

However, we do not activate this system for every transportation. And also there are certain options to it. On one hand, it could just log this data and store it in a database, e.g. for documentation. But it could also alert the customer when there are specific deviations in the parameter values that could make the goods obsolete.

How big is the share of transportations with monitoring compared to all transportations?

It is only a small share of our fleet that has monitoring capabilities because pharmaceutical company take only very little of our fleet whereas other companies have a much bigger share that rather not need monitoring of their goods. In general, it depends a lot on the customer's needs and if he is willing to pay for the service. Companies tend to put pressure on the transportation costs and if a much simpler solution does the job great and keeps the costs low, such as for instance using dry ice to keep temperatures low, they are basically not willing to take on additional costs for technology. And the more technology you put into the system, the more expensive it is.

How are the sensors implemented in the container or trailer?

It would be integrated into the trailer if it is by road or into the container if it is by sea. If it is by sea, we just buy the service from the shipping line, e.g. from Maersk. If it is by road, then we own the equipment ourselves.

How many sensors are integrated into one trailer?

There is only one sensor, measuring the container-level environment.

How are the sensors powered?

It runs on batteries, which are replaced when they are dead. And when we don't receive any more data, that is the indicator for us that it needs to be exchanged.

How are the sensors maintained?

There will be an alert if a sensor breaks down for whatever reason. And either once a day or once a week, our freight forwarder receives a report from us, in which they can see how many sensors are up and running and which require inspection or maintenance.

How does such monitoring system benefit the customer?

The selling point, at least in my perspective, is mainly to have much more transparency about the situation of their goods on our trucks. Of course, there is an agreement on how we should handle the transportation and with a monitoring system we can document if something happened, why, when, and where it happened. Furthermore, it is a quality assurance that we can deliver the goods without any major incidents or if something happens that we handle it the right way.

Do you experience any problems with the monitoring system today?

A more flexible and scalable solution would be great. What I mean is that today we have specialized trailers but it would be good to have some kind of plug-in system so that regular trailers can easily be equipped with such system. And it would be even better, to be able to just exchange or add several types of sensors. There should be some kind of standard for that, so that you can add other types of sensors if they are needed. Today, it is not really flexible because you have to buy the whole package.

And of course, it is also the cost, which has a big impact on our business.

Do you see the need for monitoring on an item level or do you think it is enough on a container or trailer level?

At the moment, there is only a need for container-level monitoring but that might be just the need of our clients. However, we divide the trailer into different sections with separating walls and then you can have different cargo temperatures. Then there can be multiple sensors in a trailer. However, this requires usually a lot of manual handling but when it optimizes the transportation, then this can be done.

But there might be the need in the future. The more detailed it gets, the better it is for the customer. This depends of course on how much the customer is willing to pay.

Appendix C

Proof of concept

This chapter shows the source code for the sensor node of the proof of concept, described in chapter 6.

Source code of sensor node

```
#include <SoftwareSerial.h>
#include <TinyGPS++.h>
#include <SHT21.h>
#include <Wire.h>


// SHT Temperature + Humidity Sensor
SHT21 sht;

// Neo-6M GPS Sensor
SoftwareSerial gpsSerial(3, 4); // RX, TX
TinyGPSPlus gps; // create gps object

// ESP8266
SoftwareSerial esp(6, 7); // RX, TX

// WiFi network connection
String ssid = "Arduino";
String password = "zse34rfv";

// Server information
String server = "192.168.43.44";
String path = "/transport-tracking/insert-data.php";

const String UUID = "839bc62d-f521-4b2e-9559-76ff80130639";


void setup() {
  Wire.begin();
  Serial.begin(9600);
  sht.begin();
  esp.begin(9600);
  gpsSerial.begin(9600);

  Serial.println("Master thesis - Sensor node - (c) Stefan Breisch");

  reset();
```

```
  connectWifi();
}

// MAIN CODE - start
void loop() {
  // get GPS data
  String location = "";

  while (gpsSerial.available() > 0) {
    int c = gpsSerial.read();

    if (gps.encode(c)) {
      if (gps.location.isValid())
      {
        location = String(gps.location.lat(), 6) + "," +
String(gps.location.lng(), 6);
      }
    }
  }

  // get temperature & humidity
  float temperature = sht.getTemperature();
  float humidity = sht.getHumidity();

  if (isnan(temperature) && isnan(humidity)) {
    Serial.println("Failed to read from SHT sensor!");
    delay(1000);
    return;
  }

  String data = "UUID=" + UUID + "&temperature=" + String(temperature) +
"&humidity=" + String(humidity) + "&location=" + location;
  Serial.println(data);
  httpRequest(server, path, data);

  // output response from ESP8266
  if (esp.available()) {
    Serial.println("ESP: " + esp.readString());
  }
  if (Serial.available()) {
    String input = Serial.readString();
    esp.println(input);
  }

  delay(10000); // delay of 10 seconds between measurement and transmission
}
```

```
// MAIN CODE - end


void reset() {
  Serial.println("Resetting ESP8266");

  esp.println("AT+RST");
  delay(1000);
  if (esp.find("OK")) {
    Serial.println("ESP8266 reset");
  }

  delay(1000);
}

void connectWifi() {
  Serial.println();
  Serial.println("Connecting to " + ssid);
  String cmd1 = "AT+CWJAP=\"" + ssid + "\",\"" + password + "\"";
  esp.println(cmd1);
  delay(4000);
  if(esp.find("OK")) {
    Serial.println("Connected!");
  } else {
    Serial.println("Cannot connect to wifi");
    connectWifi();
  }
}


void httpRequest(String IP, String path, String data) {
  Serial.println();
  String cmd2 = "AT+CIPSTART=\"TCP\",\"" + IP + "\",80";
  Serial.println(cmd2);
  esp.println(cmd2);

  delay(1000);
  if (esp.find("OK")) {
    Serial.println("TCP connection ready");
  } else {
    Serial.println("connection failed");
    esp.println("AT+CIPCLOSE");
    return;
  }

  delay(1000);
```

```
  String req = "POST " + path + " HTTP/1.0\r\n" +
               "Host: " + IP + "\r\n" +
               "Accept: *" + "/" + "*\r\n" +
               "Content-Length: " + data.length() + "\r\n" +
               "Content-Type: application/x-www-form-urlencoded\r\n" +
               "\r\n" + data;
  String cmd3 = "AT+CIPSEND=" + String(req.length());
  Serial.println(req.length());
  Serial.println(cmd3);
  esp.println(cmd3);

  delay(500);

  if (esp.find(">")) {
    Serial.println(req);
    esp.print(req);

    if (esp.find("SEND OK")) {
      Serial.println("Packet sent");

       while (esp.available()) {
        String tmpResp = esp.readString();
        Serial.println(tmpResp);
      }

      esp.println("AT+CIPCLOSE");
    }
  }
}
```