Analysis of optimal IoT system development: Life Cycle Cost (LCC) evaluation

Thomas Bracke

Supervisors: Prof. dr. ir. Sofie Verbrugge, Prof. dr. ir. Didier Colle
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Master's dissertation submitted in order to obtain the academic degree of
Master of Science in Industrial Engineering and Operations Research

Department of Information Technology
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***Abstract* – This dissertation handles on the network implementation of Internet of Things (IoT) applications. The selection of a Personal Area Network (PAN), Local Area Network (LAN) or Wide Area Network (WAN) is generically approached taking into account technical and economical motives.**

The dissertation start with an introduction on the goal and furthermore the telecommunication basics and different included networks in order to understand the following chapters. Next, the generic technical selection model is presented, followed by a generic economic selection model. Afterwards these methods are applied to 3 example cases and a sensitivity analysis is added. The first use case considers 200 000 smart containers in the port of Antwerp, in the second medication transport is monitored for 2000 trucks over some EU-countries and in the last case De Lijn, a Belgian public transport company, wants to improve their service level by tracking their arrival times.

The genericity of the technical model originates from a tree modelling approach. The economic model is generic because of its user friendly excel implementation. The use cases show the output of the models and related conclusion making. The closing sensitivity analysis paves the way for future research.

It is found that public Low Power Wide Area Networks (LPWAN) are a good approach when battery lifetimes are the most important asset. For private LPWAN additional density of the end nodes over a moderate surface is required. The exact requirements of a use case can influence these results however, therefore there is a constant competition with cellular (a WAN) approaches. Satellite never is an option, unless worldwide coverage is indispensable. PAN and LAN never compete on large scales with WAN. With smaller deployments, their exact functionality will be decisive, since among each other they differ more than WAN does.

***Keywords* – Internet of Things, Network comparison, Generic, Technical model, Economic model, Sensitivity analysis.**

I. INTRODUCTION

Internet of Things (IoT) applications are increasingly present in today's society, reports stating 20 billion devices will be in service by 2020. Their implementations range from smart agriculture to asset tracking on various scales and home automation. For each application, there are different requirements and priorities, as well as a different budget and scale. "One key questions is how these devices can be connected efficiently. " [1]

If only a few bytes per message are sufficient, existing solutions like cellular and WiFi may offer the right characteristics. They are built to support high data rates which limits their battery lifetime. Low power consumption is the key parameter on which LPWANs are built. Their goal is to reduce the total costs over the lifetime under a moto similar to "Imagine you have to replace 2 million batteries every 3 months?" On smaller scales, homes for example, new PAN and LAN solutions also exist, also enabling longer battery lives.

Of course, enabling these longer lifetimes also has downsides. For example, Sigfox (LPWAN) can send only 140 messages per day. However sometimes this is sufficient, in for example water metering, this may not be enough for other applications. Similar limitations are considered in the technical comparison, for all networks. The technical comparison is generic by its decision tree implementation.

The next question would be: what is the exact economic value of these longer battery lifetimes? For very large deployments, this becomes hard to estimate. Even more so since these longer battery lifetimes come at the cost of a higher subscription fee in the case of Sigfox, and at a high upfront cost in case or LoRA (LPWAN) where a private network is to be built by the client. Maybe, considering the scale, it is even more cost efficient to build a private WiFi network? All networks are economically compared in this dissertation by means of a model. The excel implementation of the economic model is generic because it allows user input.

The included existing networks are cellular ones (WAN), satellite connection (WAN), WiFi (LAN) and Bluetooth (PAN). The emerging ones include Sigfox (LPWAN), LoRa (LPWAN), Bluetooth Low Energy (PAN), Zigbee (LAN) and Z-Wave (LAN) among others. There number of new networks increases by the day, therefore only the ones expected to become mature and offer cost information as for today are considered in this dissertation.

For all 3 stated use cases, these networks are subjected to the technical as well as the economic comparison. Since all are large scale deployments, mostly WANs are compared. There are however attempts to include WiFi in case 1 and BLE in case 3. From the results it is very clear that these networks are not economically feasible for large scales. Furthermore, except for use case 1, cellular is always more or less competitive, even though the claims of emerging protocols.

As with all models, there are uncertainties in the input values. The impact of these uncertainties on the output of the use cases is scrutinized in the closing sensitivity analysis.

II. TECHNICAL REQUIREMENTS

An example of a technical parameter is the coverage classification in PAN, LAN and WAN. Other categories of parameters are presented here. In the dissertation, they are presented under the form of a decision tree which makes it generic.

A. Technical decision parameters

Next to coverage, the following parameters are:

1) Location of the application

Overseas, remote land area or land area.

2) Amount of end nodes in the field

3) Lifetime of the application

Can range from days to years.

4) Technical requirements

Encompasses certainty of message arrival, amount of uplink/downlink messages per day, amount of bytes per message, required data rate, real time data transmission and possible encryption of data.

5) Mobility requirements

Also location accuracy.

6) Possibility to update software over the air (OTA)

These are presented in a decision tree, for genericity reasons.

III. Economic cost model

Networks meeting the technical demands are subjected to an economic analysis. Capital expenses (CAPEX) are the upfront costs for the network, while operational expenses (OPEX) are recurring over a time basis. Their sum makes up the total cost.

Cost drivers are at the heart of an increase/decrease of the CAPEX and/or OPEX. A change in the first implicates a change in the latter. Identifying these drivers is thus the first step. Afterwards, cost information is accumulated to quantify these drivers. Sometimes cost drivers have to be calculated, the assumptions and formulas are then elaborated. An example of a calculation is: "how long does a person travel in the field to collect all the end nodes (for changing their batteries)?"

Whenever the exact magnitude of the driver is uncertain, he requires assumptions. This uncertain input is the basis of the sensitivity analysis afterwards.

Here, an introduction is given to the cost drivers. There are primary and secondary cost drivers. Secondary ones simply are more detailed or specific. The cost drivers all make up a cost category. The cost categories for CAPEX are, along with some of its primary drivers:

1) Communication chip

Primary drivers: amount of end nodes, cost price per chip.

2) Initial battery installation

Primary drivers: amount of hours and cost technical personnel (and batteries).

3) Network installation (material and required installation)

Primary drivers: technical personnel (hours, cost/hour), amount of base stations, etc.

The cost categories and some primary drivers for the OPEX are:

1) Subscription fee

Primary drivers: amount of end nodes, application lifetime.

2) Battery replacements

Primary drivers: recurrence, technical personnel (hours, cost/hour)

3) Network operation & maintenance:

Primary: location rental, amount of base stations etc.

IV. Use cases & results

As stated, there are 3 different use cases discussed in this dissertation. The decision tree is applied to each, and afterwards they are subjected to the economic model. As an example, the first use case is documented briefly here.

A. Use case 1: Port of Antwerp

The port of Antwerp wants to track their containers over the port and measure a variety of variables such as humidity, temperature, etc. In total there are 8 variables. The networks that are no longer considered suitable are Zigbee, Z-Wave Bluetooth and Bluetooth Low Energy. Primarily because their range is to limitative or the offered amount of end nodes to small. Satellite is neither considered, as it is too expensive.

The economic model returns that LoRa-private, meaning that the user builds and maintains a private network based on the LoRa protocol, is the most cost effective solution with a cost of €6.35 million. However, the downside is that the connection is limited to the port, just because it is a private network. The second best solution, Sigfox, with a cost of €9.75 million, is not yet deployed (but possibly will be). Therefore, connection outside of the port requires a cellular approach, which at its turn comes at €17.41 million.

This is an inevitable trade-off (no connection outside of the port) and similar ones apply to the remaining use cases.

B. Overall conclusions

The PAN, LAN and WAN classification gives a very good first impression of which networks to include in an economic comparison.

LPWAN has the advantage over cellular (and satellite) when battery lives offer a serious economic advantage. The setup of a use case can have a big influence here.

In an Economic comparison of Public LPWAN versus private LPWAN, the density of the amount of nodes over the surface of the area is decisive.

Often Sigfox is compared to cellular, because it is currently the only public web provider. Sigfox has the most technical limitations and this sometimes leads to trade-offs that should be decided upon by the client.

Satellite should only be used when worldwide coverage is required.

LANs are suited for small deployments. WiFi is ruled out of the comparison by LoRa-private in larger deployments. Zigbee and Z-Wave have the advantage that several automated actions are already available and this is the single decisive selection criterion for them.

PANs include Bluetooth and Bluetooth Low Energy. The former should only be used when wiring is to be eliminated. The latter when the service is proximity based.

V. Sensitivity analysis & results

Uncertainty in inputs (use case related or assumed input parameters) requires future research. The input with the highest impact are thereby the most important ones. A non-exhaustive list of such uncertain inputs is:

1) Cost price per hour of technical personnel

2) Ratio of lifetime: LPWAN vs cellular/WiFi

3) Amount of messages per day

This is user input related.

4) Influence of roaming cost for cellular networks

5) Discount obtained under economies of scale

The input parameters are assigned a statistical distribution based on their uncertainty. The output is generated for each feasible network, thus the networks considered in the use cases.

It is found that the parameters of importance differ among the different networks and as well among the use cases. Furthermore, the impact of these parameters can differ greatly. Cellular networks typically are subjected to the most variation, followed by LAN options and satellite. The results of LPWAN however are more robust to the uncertainty in the input.

The biggest impact factors, and thus these to be examined in detail in the future, are the amount of messages per day (impact on cellular), the cost of renting a location for base station deployment (private technologies), the cost of roaming (cellular), economies of scale discounts and the time to exchange a single battery in the field.

What was unexpected is that the ratio of lifetimes of LPWAN vs cellular/WiFi has little impact on the outcome. Future research should thus not primarily focus on this topic.

VI. FUTURE WORK

A. Adding increased functionality to the model

All parameters are interconnected. Relating the distance from the base station, and thus the output power of the end node with its battery consumption characteristics is not yet implemented in the model.

B. Scrutinize the uncertain parameters related to the model

Economies of scale, roaming addition, time study for battery replacement, cost of renting a location, subscription fee information, the amount of messages (use case related, simply requires more input from client).

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REFERENCES

[1] Pauls F., Krone S., Nitzold W., Fettweis G. and Flores C., URL https://mns.ifn.et.tu-dresden.de/Lists/nPublications/Attachments/927/paperVTC2013fall.pdf, accessed 26-05-2016

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Abbreviations

IoT	**I**nternet **O**f **T**hings
M2M	**M**achine To **M**achine communications
LAN	**L**ocal **A**rea **N**etwork
PAN	**P**ersonal **A**rea **N**etwork
WAN	**W**ide **A**rea **N**etwork
LPWAN	**L**ow **P**ower **W**ide **A**rea **N**etwork
BLE	**B**luetooth **L**ow **E**nergy
2G	Second **G**eneration
3G	Third **G**eneration
4G	Fourth **G**eneration
OTA	**O**ver **T**he **A**ir

Chapter 1

Introduction

Telecommunication networks are facing a widespread evolution towards the connection of everything, also known as the Internet of Things (IoT). Many published papers report the market will consist of 20 billion smart devices by 2020. Smart parking, home automation, tracking of assets (on various scales), smart metering, agriculture, maintenance facilitation are but a few examples of practical implementations, figure 1.1 shows different application areas. If a level/value can be measured by means of a sensor, which subsequently is sent to a network, a market opportunity may present itself. Lets after all not forget the market value of data in todays world. However, keep in mind that the means and efficiency of achieving this transmission can vary greatly. As such, a comparison between existing and upcoming solutions, in a framework of Machine to Machine communications (M2M), will form the topic of this paper.

Cellular as well as wired solutions, e.g. Ethernet, are already ubiquitous in todays society and immediately come to mind on the subject of data transmission. Both, among others, are preliminary used in enabling human communications (as for today). However, do they also offer the correct approach where only infrequent messages are required, as is the case of M2M communications? In a cellular solution, batteries drain quickly. Imagine replacing a million batteries, a not atypical IoT scenario, on a monthly or even quarterly basis? Personnel costs go through the roof. Imagine deploying and maintaining an Ethernet network on a nation- or even worldwide level? Is it always interesting to make such high upfront costs for wiring? This two remarks clearly highlight the financial aspect of this comparison.

It is clear that economics are an important factor in the decision making process when selecting an appropriate technology for a practical situation. Furthermore, these economic incentives are for most emerging technologies (companies) exactly their reason of existence. There is a lot of money to be made. Their focus, in contrast to existing satellite, WiFi and cellular communications for example is primarily on M2M communications. Mostly, they focus on sending small messages of only a few bytes and their whole technology is built around optimizing this feature. Although their marketing team often claims to offer the most cost effective solution for any M2M use case, this is not always the case. An example of such a misconception will be dealt with at the end of this paper, further emphasising the importance of a reliable economic comparison.

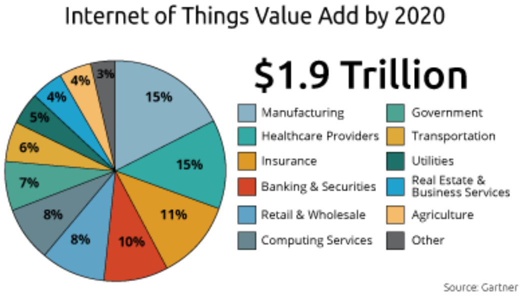

FIGURE 1.1: Application areas IoT [1]

At present, quite a few different protocols for data transmission, M2M-based or not, already exist, the most common/known ones already named in the foregoing paragraph. However when initially thinking of the fundamental difference between for example cellular and WiFi solutions, mobility of the end user immediately comes to mind. One can easily imagine more differences for which reason one or another option would not be applicable. Thus, as one can easily image there are far more parameters to be considered than solely the mobility aspect, it is possible that the most cost effective protocol/network is not even applicable because of technicalities. This highlights the technical aspect of the comparison, which is equally important as the financial aspect.

Summarized, the comparison thus has two important aspects. A technical one, where networks are eliminated because they don't meet requirements and furthermore trade offs are presented since the performance of some networks is not perfect on a certain requirement. And a second economical aspect, which is rather straightforward.

Lets now widen the scope and introduce all networks that will be compared in this paper. A range-based classification offers the most straightforward introduction. Broadly stated, Personal Area Networks (PAN) and Local Area Networks (LAN) compete against

Wide Area Networks (WAN), where range increases significantly by going from the former to the latter. In figure 1.2 a visual presentation can be found. Of course there are more protocols/network providers than those listed in figure 1.2. Especially on the LPWAN branch, which is relatively new, new competitors arise at a fast pace. Since it is impossible to include them all, a selection of the most important ones is made and especially on those where information that is necessary for this comparison, is available.

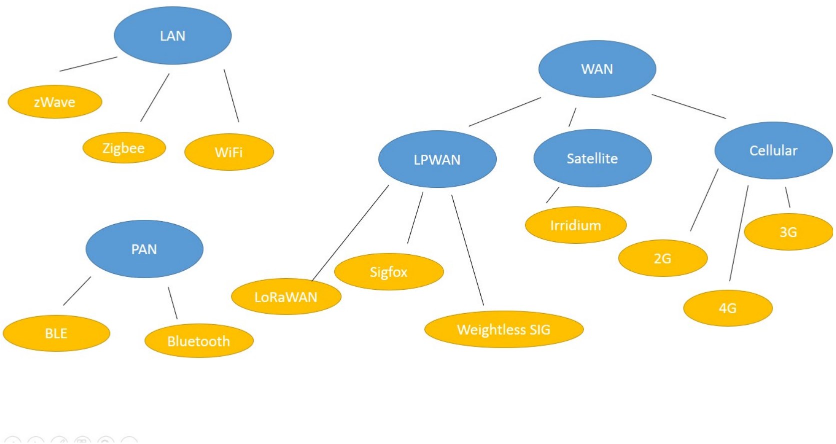

FIGURE 1.2: Classification of considered networks

Now all network options are presented, the last part of the introduction will comment on the final goal of this paper. Ultimately, all underlying material should enable an uneducated reader to make the most cost efficient decision for an arbitrary use case, of course using the presented material. Furthermore, this person should see why certain networks/protocols cannot be applied and what their trade off is.

Probably the most challenging part is contained in the word "arbitrary", since this person should be able to compare the networks on both a technical basis and an economical one. Comparison on a technical basis is possible by means of a decision tree, that guides the reader through a series of questions. The economical part consists of a model, the model will be documented and can then be used by that individual to obtain results.

Finally, as an additional part to this paper, 3 uses cases are presented and will be elaborated by means of the decision tree and model. Parameters of the economic model will then be analysed in more depth, by means of a sensitivity analysis, enabling future research.

Chapter 2

Telecommunication Basics

2.1 Transceiver/network concept: building blocks of a network

Before starting the discussion on the different available protocols and their commercially available networks, the building blocks of a telecommunication network are presented. Understanding how data is transmitted, is the first step in understanding the technical limitations of the different protocols/networks. After this section it should be clear that there are inevitable trade offs, moreover technical limitations. Dealing with tradeoffs themselves is the topic of chapter 4.

2.1.1 End node: sensor and transceiver

The end node forms the first building block in the connection process. Its architecture basically comes down to a sensor and a transceiver chip. The sensor can measure a wide range of parameters like humidity, temperature, a weight, voltage, etc, depending on the built-in electronics. Measuring more than 1 value of course has implications on the battery lifetime. The sensor is physically connected to a motherboard, an Arduino for example. On the motherboard, a Central Processing Unit (CPU) is also available for processing and decision making based on the sensor data. The CPU decides whether or not to transmit the data to the back-haul network, and if so molds it into the correct data framework, suitable for transmission. Different requirements can be set on the framework, depending on the used protocol. It is also possible to supply the CPU with more than 1 network protocol, and transmit to different networks, or select a network based on which data you have accumulated, its all up to the users preferences really. For transmission, the final step with regards to the end node, the CPU addresses the transceiver chip, also built onto the motherboard, to achieve a network connection. The transceiver chip acts like telephone number, it identifies the user towards the network and grants access. The serial number can be contained inside the chip itself, or otherwise an additional element such as a SIM-card can be required.

Now what happens after a measurement of data and possible successive transmission? The end node can go back into a sleep modus, saving power since it would only be consuming micro-Amprehours. If a realtime connection is not required for the application, this will also be the (most cost effective) case since end nodes are often battery powered. The time in between events needed to trigger a wake up of the device, are referred to as the wake up cycle. Information regarding the wake up cycle sometimes is embedded in the protocol, sometimes not and then it has to be programmed by own means. Some protocols (like for example Zigbee) already set values on when devices wake up, and for how long. Of course, small changes by the user are still possible.

An end node of a network, a sensor transceiver, in this case from Sigfox, is pictured in figure 2.1. In this case, the motherboard is not an Arduino one, but Akero is the brand name. The dimensions of such end node are, for all protocols and networks, always small, having magnitudes around several centimetres maximum.

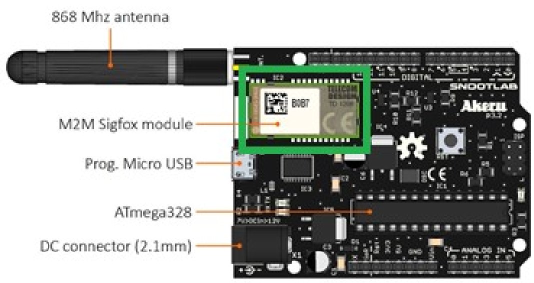

FIGURE 2.1: Example of end node with built in transceiver

The transceiver chip is framed in green in figure 2.1. A sensor can be connected to the motherboard by using the pins, and will measure the value that it is built to measure. By means of the small antenna, in this case operating in the 868 MHz band, the end node communicates with the network. Of course, the smaller the antenna, the smaller the range. However, since the antennas dimensions are comparable for all technologies, the range difference does not originate from this feature. More details will be given in section 2.3. The base station/network antenna, far larger than the end node antenna, in turn is possibly connected to a back-haul network.

2.1.2 The back-haul network

The back-haul network handles the messages such that they arrive at their intended destination. Storage of data/messages is also a possible feature offered by the technology here. What exactly is offered in the back-haul network, if there is any, differs among the technologies, mostly having financial implications to the user.

Broadly stated, the network can already be in place and accessible after subscription fees or the infrastructure has to be built by own means. Some cities can also provide free access (thus a "free subscription fee") to a city-wide available network, as is the case with WiFi in for example Helsinki, among other cities.

Summarized, the communication network always includes end nodes and one or several gateways/base stations. Additional features, like a back-haul network with cloud storage and client access to data, are optional and their availability depends on the business model of the protocol. The full option network is presented in figure 2.2.

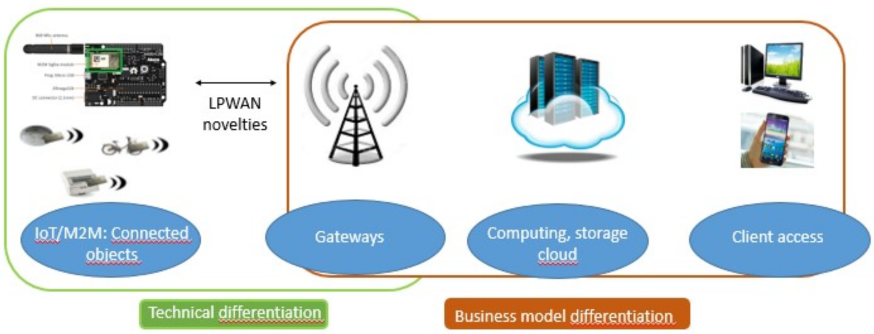

FIGURE 2.2: Full option communication network

End nodes always are a cost on behalf of the customer. The network however, including all optional features, can already be in place by the protocol owner or other instances. If the network is already in place, imagine cellular networks for example, this will be referred to as a public network. If the network has to be built and consequently maintained by the client, this will be referred to as a private network. As already stated, in the case of public networks, the customer is granted access by paying subscription fees. In the case of private networks, this cost is absent but replaced by the deployment and maintenance cost of the network. The business model of the companies thus relate to the costs the customer has to make, and in some cases give birth to so called cost drivers. These cost drivers will be examined in detail later, when building the cost model.

2.2 Parameters considered

Before listing the different parameters and explaining their significance to this paper, lets first decide where these so called parameters fit in the structure. In chapter 1, a classification of networks was presented in figure 1.2. The division in categories (PAN, LAN, WAN) is a range-based one, chosen because it is easy comprehensible to any reader. Also in chapter 1, there is stated to be a technical part of the paper, which will ultimately take the shape of a decision tree/series of questions. Now what exactly is the link between the decision tree and this division in categories? The range division is actually the first parameter that is to be considered. In this context, parameters are the technical differences among the different protocols/networks and they lie at the basis of the decision tree, since its questions will all be related to a certain parameter. As will be elaborated, most of the parameters also have economical implications. Finally, most parameters are interconnected, which will be documented in section 2.3.

Range clearly is the first parameter. Its economical implication is in the network deployment phase. The bigger the range around a single base station of the network, the less base stations have to be foreseen to cover a certain area. Ranges go from several metres (e.g. Bluetooth), to 50 kilometres (Sigfox) or even to worldwide coverage (satellite).

Battery life is the second decision parameter, also having economical implications. The longer the battery life for a certain protocol, the lower the costs of technical personnel replacing them. Battery life of course depends on the usage of the device, but at similar usage intensity, ranges go from several days-weeks (e.g. Bluetooth, cellular, WiFi) to almost a decade (typically LPWAN).

Some applications can be based indoor, others outdoors. The ranges stated online often are the outdoor ones, simply because they are larger and it is better for business. It is however very easy to see through this marketing technique and the distinguishing parameter here is named "indoor penetration". Indoor penetration gives information on how good or how bad the transmission of a certain network is in penetrating construction materials like reinforced concrete for example. Construction materials typically hinder the signal and it is safe to say that broadband signal suffer more from this physical law. In addition to that, penetration characteristics are always better for lower frequency waves. This will further be elaborated in section 2.3. Indoor penetration can be quantified in dBm, but little information/studies are available on this topic. However, there is information available if you would want to subdivide the networks in categories like easy, medium and high.

Secure transmissions can be of major importance. For example consider a production facility where the transmitted data includes lead times of their production. Needless to say, this data has high economic value to the competition. In contrast, a farmer tracking in his cows, probably does not attach the same value to his transmitted information. AES 128 encryption is the most common fashion of securing data and is used by many protocols. As the name says, it uses 128 bits solely for encrypting data, and this might just be too much for narrow-band technologies which have only a few bytes available for one transmission.

Also in the tracking of moving assets, differences arise. First of all, objects can be moving or not and some protocols would already drop out of the comparison. Furthermore, the speed can be decisive as well. Applications on high speed trains travelling at 300 kilometers an hour do not have many options left but cellular or satellite connection. In the same context of asset tracking, there is location accuracy. Variations as big as accuracy upon 1 meter until several hundred meters exist, which also can be a crucial element. Location accuracy is achieved by triangulation. This technique only works with broadband technologies, this information is supplied by industry experts.

Typically in some LAN networks, the amount of transceiver devices is limited to around 100 or less in practical implementations. Of course this is not sufficient for nationwide applications. Thus the amount of devices per base station has an influence as well.

It should be clear that this is mainly because of economic reasons that originate in deployment.

Some of the LPWAN technologies also offer the possibility to perform updates over the air, updating the version of the protocol or simply altering the code to send out other data, or to present the data in another format in the future. Technologies such as WiFi for example, where high data rates are available, naturally offer this feature, as the primary requirement is adequate data rates to perform this transaction in time (legislation sometimes limits time on the air of transmissions). If such updates are not possible, upgrades would to be done manually. For larger networks, this would be a major cost, as the update manually has to be applied to each end node separately. And therefore can influence the selection process if you expect to perform these updates throughout the lifetime of your application.

The last parameter considered is roaming. Roaming is a general term in wireless telecommunication in which a particular service is continued even though the user is not in the network in which it is registered. Enabled roaming can offer cost advantages when the scale of the application is sufficiently large, ranging over different nations.

2.3 Parameters relations/trade-offs

Transceiver end nodes emit and receive information by means electromagnetic waves carrying information in the form of bits. Frequency bands of these waves are bound to very strict legislation regarding spectrum allocations, duty cycle limitations as well as emission power constraints. Allocated frequencies in higher spectra, for example the 2.4 GHz band, tend to be larger, which from an observer viewpoint can be explained as: there simply is more bandwidth available in these higher spectra with similar characteristics. In a practical context, the higher the available bandwidth, the higher the data rates achievable, regardless of the modulation technique. Summarized, the higher the operational frequency, the larger the bandwidth and thus the higher the data rates, which essentially results from legislatively allocated frequency bands.

Next to the legislation, there are the physical characterizations of electromagnetic waves, as already mentioned in the previous section. As with any wave, the lower its frequency, the further it travels for the same output power, thus extending its range. This can be compared to a high pitch sound wave versus a bass sound wave in music. Whenever theres a noisy party nearby, its the bass that you will hear, not the high tones. Thus, returning to electromagnetic waves, protocols operating in lower frequency bands will achieve higher ranges for the same output power. In physics, this is known as the Friis Transmission Equation [2]. Furthermore remark that the output power of a transceiver device is coupled to its battery life and therefore, operating in lower frequency bands therefore facilitates obtaining longer battery lives, whilst maintaining the same range. Additionally, as already stated, there is a connection between indoor penetration and the operating frequency. The lower the frequency band, the better its penetration of construction materials. Furthermore, also on the topic of indoor penetration, slower transmission on signals further enhances the indoor penetration. This way lower bandwidths are directly related to better penetration characteristics.

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4R}\right)^2 \tag{2.1}$$

Above is the Friss transmission equation. P is the output power of receiving and transmitting antenna; G the antenna gains of receiving and transmitting antenna; λ is the wavelength of electromagnetic wave, inversly proportional to the frequency and R presents the distance between receiving and transmitting antenna.

Summarized, following parameters are interconnected: indoor penetration, range and battery life. On a very high level, the connection between them is the data rate, or in other words the bandwidth. The higher the bandwidth, the lower its range and indoor penetration, and the smaller the battery life. To some extend, this is also linked to data security, since low bandwidths do not allow 128 AES encryption.

Now it should be clear that it is impossible to achieve the best performance on all technical aspects. This is the reason that differences among the categories arise. They use the parameters in a way that they see most fit for the market they target. In the following chapter, the parameters will be quantified and the different technologies will be documented in detail. After mapping the parameters on the protocols, the decision tree is addressed.

Chapter 3

Protocols and their characteristics

Returning to the range classification, PANs and LANs consistently have a range that is limited to around 100 meters in rural landscapes, often even lower for PANs, although it can be extended by some means and under some circumstances, which will be reviewed when those networks are discussed. Wide Area networks offer a much wider coverage, ranging from city level to worldwide coverage since they cover a radius of 5 to 10 kilometres on each side of their base station. This range based approach will also be used in this chapter.

The parameters described in chapter 2 are summarized/quantified in tables 3.1, 3.2 and 3.3 for the different classifications. Because sometimes the interpretation is somewhat more nuanced in order to determine whether or not a certain network is suited for a certain application, the necessary comments are provided for each network in the corresponding section.

A comment that might be useful before starting the discussion is on what the different possibilities are using these devices. It is possible to solely collect data, measured by the sensors. In this case the user has to program himself what values that are to be sent over the network, and therefore a similar amount of programming is required here and this is not considered in the comparison. A second option is to automate actions. In this case as well, the user has to program the required logic. The only exceptions to this are Zigbee and Z-Wave where to programming is already done. They are fully functional after you buy them. The end nodes of these 2 technologies are typically also more expensive because of this reason. Since these two however are typically used in other applications, this requirement of programming also will not be considered in this paper.

3.1 Personal Area Networks - PAN

3.1.1 Bluetooth

"Bluetooth is a wireless technology standard for exchanging data over short distances (using short-wavelength UHF radio waves in the ISM band from 2.4 to 2.485 GHz) from fixed and mobile devices, and building personal area networks (PANs). Invented by telecomvendor Ericsson in 1994, it was originally conceived as a wireless alternative to RS-232 data cables. It can connect several devices, overcoming problems of synchronization." The protocol is known in the jargon as v3.0. [3]

Referring to figure 2.2, a Bluetooth network does not compromise a back-haul network, neither a data access point. The transceivers are bought by the client and typically are included inside another device. As already stated the purpose is to connect this device wirelessly to another device. The connection stands for as long as the client desires or until the battery is drained. Typical devices are smartphones, speakers, computer mouse, etc.

In connecting devices over Bluetooth, there is one master device and the rest will be slave devices. The master initiates all actions in transmission, rather than sending requests. The amount of nodes that can connect to a single master-slave network is limited to 8, including the master. The setup of the connection is manual instead of automated. Additionally to the limited amount of devices in a single network, the range of the connection is restricted to several metres. Therefore, IoT solutions over Bluetooth are confined to the area compromising several metres around the master device. Mobile applications are possible, provided that both the master and slave devices stay close together, such that the connection does not breach.

All together, this makes Bluetooth suited for wireless connection of devices in its immediate surroundings, where high data rates are possible.

3.1.2 Bluetooth Low Energy - BLE

Bluetooth saw the shortcomings of their v3.0 protocol for the upcoming IoT market. They developed a new protocol, v4.0, more commonly known as Bluetooth Low Energy (BLE). The v4.0 protocol compromises all features of the previous protocols, such that it would be possible to operate in that v3.0 mode, but those are not required for the new market they aim at.

It might be useful to note that all smartphones (where the major amount of BLE transceivers is represented) currently brought to the market all carry the v4.0 protocol stack, and even though there are only few applications nowadays, the moment Bluetooth does develop more applications, the deployment can go very fast. It should be noted that Bluetooth keeps an open protocol, thus anyone can contribute to the protocol. More specifically, anyone can develop an application and upload it onto their beacon.

As for the v4.0 protocol, thus their "Low Energy" variant, a beacon constantly transmits a same signal, moreover it always contains the same information. The nature of this information is completely as the client desires. The end node will receive this signal and will mostly be embedded in a smartphone, although it is very easy to implement a sensor solution on a motherboard.

The purpose of transmission is different than with the v3.0 stack. When transmitting a signal (in practical situations with a frequency of 0.1 to 10 Hz, client specified), the beacon does not necessarily aim at establishing a connection between itself and the end node. Rather, it wants to alert the end nodes of its presence. The end node will always transmit back its presence. At this stage it is possible for the beacon to ask for an established connection, which is as the owner of the beacon desires. The end node can accept or either decline the connection. Upon accepting, data is sent exchanged using the v3.0 protocol stack. The data exchanged can for example be an URL, opening the URL will then proceed over WiFi or cellular, no longer using the BLE protocol since BLE does not grant access to the worldwide internet network. With this policy, Bluetooth Low Energy aims at markets where detecting presence is of major importance, and this will from now on be described as proximity services.

The range of the beacon typically is limited to several metres, thus explaining the name "proximity services", practically around 5 metres. The range is this low because of the small emission power of the beacon device. The user can extend this range to say 100 metres. When extending the range however, the battery life of several years drops to the magnitude of weeks. It is thus clear that the v4.0 stack focuses on small messages, in a limited range to enable long battery lives. A typical use case could be detecting the long time presence of a customer in an alley of a store. This could indicate that they do not find their product, and a shop assistant could come to help.

When deploying a BLE network, it only compromises a beacon since a further back-haul network is not included in the package, thus data storage is on account of the person placing the beacon. Typical use cases however, do not per se require data storage.

3.2 Local Area Networks - LAN

Local area networks typically have ranges around 100 metres in rural settings. In home applied situations, they already have found widespread use for many years. LAN networks are also the most diversified of all networks mentioned here, more specifically the different protocols all focus on different implementations. All of the protocols are commercially available. Which enables fast deployment, if necessary.

3.2.1 WiFi

Very widespread in use, there are numerous of networks already in place over the world. All protocols are based on the international IEEE802.11 specification, although they mutually differ in exact parameter values like data rates, maximum packet length etc. Their magnitudes however are all broadly the same and thus in table 3.1 it are rather the magnitudes that are important.

A WiFi network grants access to the worldwide web by paying a subscription fee to a national internet provider. Thus all parts up till the back-haul network are included in figure 2.2. The routers of the WiFi network are considered base stations. Data storage is on the account of the customer, however online data centers such as Amazon are easily available, at very low prices. Formatting the data in the correct template however will require some effort, since the data has to be sent over IP.

The network typically is private, meaning that the routers are privately held and only accessible for parties owning the private key, but also public networks exist. In for example Niue, free WiFi is available throughout the country. A national network is in place and free access is granted to its citizens. Such availability can severely influence the costs of implementing an IoT application over WiFi and suddenly make large scale, long life deployments feasible.

WiFi is not applicable when fast moving devices are required. Namely, the transceiver device sets up a connection channel with the WiFi router and the setup requires several seconds, in which the device can already have moved out of the range of the router. He might be inside the range of a following router, but the setup has to start over, disabling connection potential. At moderate speeds though, there will be no problems for this connection. It should be noted that the duration of this setup is exactly the reason for the shorter battery lifetimes. Of course, this last notion is if the end node still has to wake up as well.

WiFi secures data packets using the IP protocol encryption. This adds overhead to the datapacket, but seen its data rates this invokes no further problems.

From the above, the conclusion is that the WiFi option is predominantly suited for stationary/local applications requiring high data rates, where battery lifetimes are not a major concern. The scale of the network is preferably small, because of installation costs. In a framework of IoT, data accumulation is the primary goal of this network.

A last note on this section: WiMAX is not considered. WiMAX can transmit WiFi signals over large distances, in the magnitude of several kilometres. However, it solely connects 2 towers, granting the second one internet connection by means of the connection of the first tower. The WiMAX router however, does not grant coverage over an area. This is what distinguishes it from all technologies here and why it is not considered.

3.2.2 Zigbee

Some quotes accurately describe the goal of Zigbee, and how it functions. Afterwards, some additional comments will clearify the remainder.

"ZigBee[1] is an IEEE 802.15.4-based specification for a suite of high-level communication protocols used to create Local Area Networks. It is intended to replace WiFi and Bluetooth for purposes of home automation." [4]

"ZigBee operates in the ISM radio bands, and it defines a general-purpose, inexpensive, self-organizing, mesh network for industrial control, embedded sensing, medical data collection, smoke and intruder warning, building automation and home automation." [5]

"Its low power consumption limits transmission distances to 10100 meters line-of-sight, depending on power output and environmental characteristics. ZigBee devices can transmit data over long distances by passing data through a mesh network of intermediate devices to reach more distant ones." [4]

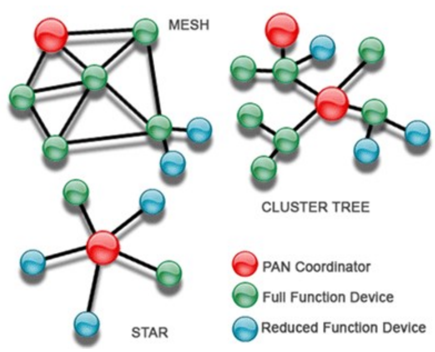

FIGURE 3.1: Zigbee meshing network topology [5]

In this meshing topology, devices classified as repeaters retransmit a received signal, thereby extending the range of the network. A single device has a range of around 70 metres line of sight, adding a repeater each time adds up an additional 70 metres line of sight (140 considering both sides of the repeater). Zigbee classifies these devices as "full function devices". Mostly those are not battery powered, since they can not enter sleep mode and would be to power consuming. In addition to the repeaters, each network contains transceivers (as any other network presented here), and a single master coordinator per network. The master devices stores information on optimal routes between repeaters and receivers. As much as meshing is an advantage, it also limits the possibilities. Each network master can connect up to 256 end devices, but this includes repeaters as well. Thus when enabling larger ranges by meshing, the possible amount of transceivers lowers correspondingly. In addition, the master stores path information, but as soon as a transceiver is relocated in the network, this path changes and has to be updated, thus meanwhile, this node cannot be operative. Furthermore, after being relocated, the transceiver has to be connected to the network again manually by pushing a button, since a nearby repeater will not automatically recognise a new transceiver.

[1] http://www.zigbee.org/

Zigbee network elements can be bought from international partners such as Microchip, Texas Instruments, Silicon Labs, etc. The setup of the network is very straightforward, as already mentioned, a simple push on the button of a Zigbee device activates it.

The network is very suited for home applications, where the wiring of repeaters is not too cumbersome. Furthermore, outdoor applications are possible, as long as the amount of devices is limited, as well as the devices are not moving. The network is not suited for storing data, but rather for automation of recurring tasks.

3.2.3 zWave

Z-Wave [2] is very similar to Zigbee in all its aspects. It also operates a meshing network where transceivers have to be recognised and is very suited for home automation. There exist 2 major differences between the networks. First Z-Wave operates in ISM bands, while Zigbee operates in the 2.4GHz band. They say this limits interference with WiFi networks, which optionally also operate in the 2.4GHz band. Secondly, as Z-Wave also is limited in amount of devices per network (232), Z-Wave offers the option of network bridging [3] , where 2 or more meshing networks can be connected. This way it is possible to built larger networks where needed. Although the possibility exists, it still is not a very neat approach for large networks. The programming for enabling meshing between the 2 or more different networks still has to be done, however there is no information on the difficulty. Furthermore, since it also uses a meshing approach, the range is again limited to the magnitude of metres and extension of the range goes at the cost of having to wire the repeaters.

FIGURE 3.2: Z-Wave home automation [6]

We can conclude that Z-Wave and Zigbee can be used in similar use cases. Where more than 256 devices are needed, Z-Wave is to be preferred.

[2] http://www.z-wave.com/

[3] https://en.wikipedia.org/wiki/Bridging_(networking)

3.3 Cellular and Satellite

3.3.1 Cellular

Cellular networks have been around for quite some time now. The first protocol that can be of any importance in this paper is the so called "2nd Generation", where is became possible to send text messages. Nowadays, more advanced protocols such as the "3rd Generation" and "4th Generation" are available, their main surplus is in the fact that they offer higher data rates as well as Internet access.

Cellular communications happen over transceiving antennas, which are in most cases nationally deployed by a telecommunication provider. Again referring to figure 2.2, the back-haul network is provided by the network provider, as well as the base stations. Data handling however in on account of the customer. Roaming is in most cases an expensive addition to the subscription fee, thus for applications ranging over more than 1 nation, this issue should be considered. As well on the topic of the network specifics, it is possible that the network is not deployed in certain regions. For example overseas, on remote areas and some underdeveloped countries, the network is not deployed. Deploying a new cellular network for those regions involves a series of legislative procedures and this option will not be considered in this paper.

These networks are very similar to the emerging LPWAN technologies. They have the same range in terms of magnitudes, they can be used for sending only small messages, they encrypt their data, they support mobile applications (even up to speeds of high speed trains), they provide coverage to very large areas, etc. The major difference between these options is the battery life, and thus the economic incentive for choosing an LPWAN technology is the replacement cost of the batteries in large networks. These devices however can well be programmed to enter a sleep mode when they are not transmitting or receiving, this is however a very interesting point in this paper since it is not always optimal to enter sleep mode for cellular networks and its details are explained in section 5.3.6.3. Furthermore it is possible to pack several data values in a single message, known as a telemetric approach. Thus for example transmitting only once, with the data of 5 messages in that single transmission. The connection time to the network, when establishing a so called "network handshake", takes longer than LPWAN and consumes more energy per unit of time than for LPWAN technologies, thereby draining their battery lives. The establishment of the connection is the most energy consuming phase of the transmission process with cellular networks.

In contrast to LPWAN technologies, they offer the advantage of larger data rates, but for most IoT applications it is questionable whether this is required or not. An additional advantage can be that the network has already proven its value in Peer 2 Peer communications. It can thus be concluded that these networks are very suited for data accumulation, and that in most cases, a cost analysis will be decisive in choosing between LPWAN and cellular options.

3.3.2 Satellite

Satellite communications are very similar to cellular ones. Their coverage however is extended to a world scale instead of nations. There are several major providers of satellite networks over the world, some well known world wide (or near) providers include Eutelsat and Iridium. In this paper, cost and technical data for the Iridium network is taken, including other satellite operators would not offer any added value, as the results would differ only very little from those obtained for Iridium.

Satellite communications offer the advantage of being available worldwide. They offer very similar characteristics to cellular solutions and therefore have the advantage of coverage over them. A disadvantage is that a non-clear sky, thus line of sight towards the satellite, can limit the network availability. Furthermore, the subscription cost to connect to the network is much higher than the cellular case. Thus the satellite option will practically only be used when the cellular option is not available at the site of operations.

3.4 Low Power Wide Area Networks - LPWAN

Low Power Wide Area networks are similar to cellular communications qua network topology. They both operate in a star network where a centralized base station acquires and sends messages from and to transceivers. They focus on different parameters although. Cellular communications are optimized towards data rates whereas LPWAN focus on long battery lives. The way the different LPWANs achieve this, will be explained in the following sections. Furthermore, LPWAN technologies all operate in the ISM bands, being sub-GHz. Cellular providers operate mostly in the 2.4 GHz band, which offers higher data rates, but reduced indoor penetration.

As common characteristics among LPWANs, following are noted: high range, long battery lives, low battery power consumption, ISM frequency band, base station cooperation for wide area coverage and high amounts of end devices.

Topics they differ upon: Exact method of achieving long battery lives(all via sleep modes though), Roaming policy, deployment status and commercial availability, Service Level Agreements (SLA), encryption, datarates , over the air updates possibility, openness of protocol, private vs public networks.

3.4.1 Sigfox

Sigfox aims at becoming the global leader as LPWAN network provider. Currently they are deploying their base stations at a very fast rate, already having covered over 1.2 million km^2 in 14 countries, mainly Europe. The status of their deployment continually changes and can be tracked on their website. [4] Since they are in charge of their own network, roaming is included in the subscription fee business model and does not come with an additional cost. Furthermore, data send over the Sigfox network is saved on their servers and can be accessed at any time, without additional charge.

The Sigfox protocol is tightly held by the Sigfox company, and it is not open in contrast to the other LPWANs presented here. The transceivers are manufactured by a wide range of well established companies including for example Texas Instruments and Silicon Labs. Since the protocol is not open, data always has to be formatted in the 12 byte framework. It would be possible to augment this 12 bytes, if the protocol were open, by changing the datarate of 100 bits per second.

As all other LPWAN technologies they operate in ISM bands, to enable longer ranges and enhance indoor penetration. They even further extend this range by transmitting at very low data rates, namely 100 bit per second. This is a consequence of operating in very narrow channel bandwidths. Their applied modulation is called Ultra Narrow

[4] http://www.sigfox.com/

Band (UNB), they state "The slower you transmit, the better you are heard". Because of this UNB they gain 2 advantages: enhanced range for the same output power, and enhanced indoor penetration for the same output power. Additionally, they can connect up to 1 million transceivers to a single base station. This also is a consequence of the small bandwidth. They claim this technique also suffers less from interference, although opposite claims are made by their rival companies.

UNB does not only offer advantages. Due to the slow data rates, their messages spent a long time over the air. In ISM bands, there is strict legislation on transmission duty cycles (this is not the case in the 2.4GHz band used by cellular and WiFi technologies). Because of their low data rates, Sigfox end nodes require 2 seconds to send 1 message (1 message is a total of 12 bytes, see table 3.3). European legislation states that devices in ISM bands can only transmit during 840 seconds per day. In addition to their slow data rates, they send each message 3 times because they don't make a network handshake but they do wish to offer a certain Service Level Agreement, allegedly each message having a certainty of arrival of around 97%. Sending a message 3 times, their SLA increases to 99.9973%, and each message requires 6 seconds of the 840 seconds per day transmission time. This comes down to 140 messages per day, an aspect that needs to be taken into consideration when selecting this network for an application. Summarized the limitations of the Sigfox protocol are the fact that a message can only contain 12 bytes, that you are never a 100 percent certain that a message will arrive at its destination and that you can only send 140 messages per day per device.

Further on the origin of the arrival uncertainty, it follows from the fact that the device does not set up a communication channel with the base station, there is no "network handshake". The device simply wakes up out of its sleep mode and transmits the message, then hopes that the message will arrive at a nearby base station. Therefore, hand off is not an issue in this protocol.

3.4.2 LoRa

LoRa also aims at becoming a global player on the landscape of LPWANs. The only fabricant of chips is Semtech, and they also are the owner of the protocol. Because Semtech is the only providor of LoRa chips worldwide, they price them at around 5 euros, while chips using the Sigfox protocol are around 2 euros because of intense competition between different manufacturers.

LoRa is the commercial name that covers all physical network elements (bought at Semtech) as well as the protocol. The name of the open protocol is named LoRaWAN and anyone can make contributions to it. There are different private protocols as well, based on LoRaWAN. They are owned by private companies and typically have enabled small additional features. An example of such a company is Symphony Link. They enabled updates over the air in the protocol, as well as end nodes acting as repeaters and meshing between base stations, which requires around 12 months of programming for a single person. You can buy solutions from them, at a higher price, but you do profit from their additional features in the protocol. Privately held protocols like Symphony Link will not be considered in this paper, only LoRaWAN will be.

LoRa offers similar ranges to Sigfox, as in several kilometres, but they are slightly lower, however high enough to offer solutions to similar applications. Their battery lives are also very comparable and in the magnitude of years, depending on the usage of the end node.

In addition to an open protocol, LoRa or rather Semtech in this context, allows setting up private networks. Base stations are bought, and the deployment is on behalf of the customer. This way, there are several national telecommunication operators now installing a nationwide "public" LoRa network, like Proximus in Belgium and KPNG in the Netherlands. The future still has to point out their subscription fees, since those are not publicly known yet. If you built a private network, everything is on your behalf. You have to enable meshing and such between base stations, as well as take care of data storage. If you would choose for a public network provider, this will all be included in a subscription fee.

LoRa transceivers do, in contrast to Sigfox, make a network handshake. Therefore you are a 100 percent sure that the message will effectively arrive. The handshake goes very quick, in contrast to cellular and WiFi end nodes which take a long time to connect, which enables long battery lives. The data rates of LoRa transceivers are several order of magnitude larger than for Sigfox ones, therefore they do not suffer from the legislative limitations on duty cycles since their time over the air when sending a message is in the milliseconds and the amount of messages per day is practically unlimited.

With LoRa you can choose the operating mode of your transceiver. These are classified as either A, B or C and can be described as:

- "Bi-directional end-devices (Class A): End-devices of Class A allow for bi directional communications whereby each end-device's up-link transmission is followed by two short down-link receive windows. The transmission slot scheduled by the end-device is based on its own communication needs with a small variation based on a random time basis (ALOHA-type of protocol). This Class A operation is the lowest power end-device system for applications that only require down-link communication from the server shortly after the end-device has sent an up-link transmission. Down-link communications from the server at any other time will have to wait until the next scheduled up-link." [7]
- "Bi-directional end-devices with scheduled receive slots (Class B): In addition to the Class A random receive windows, Class B devices open extra receive windows at scheduled times. In order for the End-device to open its receive window at the scheduled time it receives a time synchronized Beacon from the gateway. This allows the server to know when the end-device is listening." [7]
- "Bi-directional end-devices with maximal receive slots (Class C): End-devices of Class C have nearly continuously open receive windows, only closed when transmitting." [7]

From the foregoing listing, it is thus safe to assume that Symphony Link uses class C devices as repeaters. It is clear that these repeater like devices should be wired, since their battery lives are only days to weeks otherwise.

Because they operate with higher data rates, their bandwidth has to be larger. They do not operate using UNB but rather Spread Spectrum (SS). Consequently to the higher channel bandwidth, not as many devices can connect to a single base station at once, namely 65 thousand. This can be an important factor when building your own network. Furthermore, only 8 devices can connect to the base station at once, again due to bandwidth limitations. But the protocol assures that this will not hinder communications since a device will simply go back to sleep and transmit at a later time when the base station is currently not available. Since the data rates are high and thus transmission takes only a short time, this is a plausible statement.

Summarized, LoRa is, as Sigfox is, very suited for collecting data, as well as automation of actions. They offer the option of private networks, which can be interesting if you want to cover an area spanning several km^2 with some thousands of end nodes. Of course, an economic comparison will be decisive on this aspect. It is however so that LoRa should be used when the amount of messages exceeds 140, since Sigfox is no longer applicable then. Furthermore, they offer long battery lives, which is an advantage over cellular networks. Actually, these networks can be considered similar to cellular ones, and thus suited for similar applications, but with longer battery lives. Or otherwise, compared to WiFi networks with greater coverage possiblities and longer lifetimes.

3.4.3 Weightless - nWave

Weightless also forms a protocol that is very promising to the future. There is however, much less known about this protocol in comparison with the previous two LPWAN protocols. Furthermore, since Weightless is a open standard, governed by the non-profit body Weightless SIG, the commercial implementation of the protocol does not happen by this party, but rather by nWave (who for the record contributes in the further development and improvement of the protocol). Their commercial activities so far have been limited to 2 cities in Denmark, namely Esbjerg and Copenhagen. [8] They deploy networks using only the Weightless-N device. As can be seen in table 3.3, Weightless also offers protocols for type -W and -P devices. The type -P device is not in operation, and the reason can not be named. As for the type -W device, the author contacted the Weightless SIG company. It comes down to the fact that they hoped to operate in white space spectrum, which also is sub-GHz like ISM bands, but there is more available. Due to regulations, they could not operate in these bands, although they had hoped for it while developing the protocol. So now the device is more or less useless.

Their type -N device is very similar to Sigfox, thus supposedly, they can be used in very similar use cases. There are however some fact that are unclear. Does their device perform a network handshake? Do they operate under a subscription fee model? Is it possible to build a private network? Where are they planning on deploying? What is their roaming policy? etc. Due to these series of questions, it is not possible to take Weightless into account in the decision tree of the following chapter. It however is a very promising protocol, and future research should definitely take it into account when more information is available.

3.4.4 DASH7

The DASH7 [5] protocol also is an open protocol, owned by the non-profit body DASH7 Alliance. About the commercial status of this protocol, even less is known than for the Weightless one. The technical data that already is public, is summarized in table 3.3. However additional information is required to include the protocol in the decision tree. For this reason, the protocol will not be considered in this paper but it might be interesting for future research.

3.4.5 Remaining protocols

As stated in chapter 1 there are are various reports that the IoT market will consist of a huge amount of devices by 2020. Bluntly said, because there is a lot of money to be made, a lot of parties are interested. Since the LPWAN approach is very suited for data accumulation, there are lots of new protocols arising at a fast pace. Here some of the most developed ones (as for today) have been discussed and even among these, there is only sufficient information for 2 of them to include them fully in this paper. For this reason, others will not be included in this paper, although they might be relevant options in the future. A non-restrictive list of such protocols/networks with potential are RPMA, Ingenu, NB-FI, ...

[5] http://www.dash7-alliance.org/

Table 3.1: Parameter values for PAN and LAN protocols

Classification		PAN		LAN		
Protocol		Bluetooth	BLE	WiFi	Zigbee	zWave
Device type						
Commercially available?	[-]	Y	Y	Y	Y	Y
Smaller variants to protocol available?	[Y/N]	+-Y	+-Y	Y	N	N
Commercial providor - network		Bluetooth SIG	Bluetooth SIG	Multiple	Zigbee	zWave
Commercial providor - Transceiver		Multiple	Multiple	Multiple	Multiple?	Multiple?
Public/private network		Private	Public	Both	Private	Private
Frequency band	[Hz]	2,4G	2,4G	2,4G/5,8G	(ISM)/2.4G	ISM
Channel bandwidth	[Hz]	1M	1M	Protocol dependent	2M	300k/400k
Transceivers/Base Station	[-]	7		?	65536 (not in practice)	256
Range - urban	[m]	1 - 100	5	10-30	10 - 50	50
Range - rural	[m]	1 - 100	Irrelevant	100	70	100
(Max) data rate - uplink	[bps]	1M - 3M	1M	Protocol dependent	20k/40k/250k	100
(Max) data rate - downlink	[bps]	1M - 3M	1M	Protocol dependent	20k/40k/250k	100
Max messages/day - uplink	[-]	Unlimited	Unlimited	Unlimited	Unlimited	Unlimited
Max messages/day - downlink	[-]	Unlimited	Unlimited	Unlimited	Unlimited	Unlimited
(Max) packet length - uplink	[bytes]	1024		Protocol dependent	133 (33 overhead)	64 (15 - 33 overhead)
(Max) packet size - downlink	[bytes]	1024		Protocol dependent	133 (33 overhead)	64 (15 - 33 overhead)
Encryption	[-]	?	128 AES	IP	128 AES	?
Battery life - magnitude indication	[-]	Days - Weeks	Years	Days - weeks	Years	Years
Roaming in package?	[Y/N]	N, Irrelevant	Irrelevant	Y	N, Irrelevant	N, Irrelevant

TABLE 3.2: Parameter values for cellular protocols

Classification		Cellular			Sattelite
Protocol		2G	3G	4G	Sattelite
Device type					
Commercially available?	[-]	Y	Y	Y	Y
Smaller variants to protocol available?	[Y/N]	Y	Y	Y	Y
Commercial providor - network		Several	Several	Several	Several
Commercial providor - Transceiver		Several	Several	Several	Several, Irridium here
Public/private network		Public	Public	Public	Public
Frequency band	[Hz]	800M/1900M	800M/1900/2100M	800M/1900M/2100M/2500M	1616M-1626,5M
Channel bandwidth	[Hz]	200k	1,25M	5M - 20M	
Transceivers/Base Station	[-]	?	?	?	?
Range - urban	[m]	1k - 2k	1k - 2k	1k - 2k	Irrelevant
Range - rural	[m]	several k	several k	several k	Irrelevant
(Max) data rate - uplink	[bps]	500k	3,1M	100M (highly mobile), 1G (stationary)	10k
(Max) data rate - downlink	[bps]	500k	3,1M	100M (highly mobile), 1G (stationary)	2300?
Max messages/day - uplink	[-]	Unlimited	Unlimited	Unlimited	Unlimited?
Max messages/day - downlink	[-]	Unlimited	Unlimited	Unlimited	Unlimited?
(Max) packet length - uplink	[bytes]	1500?	512	1500? (variable)	1000
(Max) packet size - downlink	[bytes]	1500?	512	1500? (variable)	1000
Encryption	[-]	A5	128 AES	Ipsec	
Battery life - magnitude indication	[-]	Weeks	Weeks	Weeks	Weeks
Roaming in package?	[Y/N]	Y	Y	Y	Y

TABLE 3.3: Parameter values for LPWAN protocols

Classification		LPWAN					
Protocol		Sigfox	LoRaWAN	Weightless			DASH7
Device type				W	N	P	
Commercially available?	[-]	Y	Y	N	Limited?	?	N
Smaller variants to protocol available?	[Y/N]	N	Y	?	?	?	?
Commercial providor - network		Sigfox	National partner	?	nWave		?
Commercial providor - Transceiver		Several	Semtech	?	nWave?	?	?
Public/private network		Public	Both	?	?	?	?
Frequency band	[Hz]	ISM	ISM	TV whitespace	ISM	ISM	ISM
Channel bandwidth	[Hz]	100	EU: 8x125k US: 64x125k	5M	200	12,5k	25k or 200k
Transceivers/Base Station	[-]	1M	64000	Unlimited (?)	Unlimited (?)	Unlimited (?)	?
Range - urban	[m]	10k	2k - 5k	5k	2k	2k	?
Range - rural	[m]	30k - 50k	15k	?	?	?	5k
(Max) data rate - uplink	[bps]	100	EU: 300 - 50 k US: 900 - 100k	1k - 10M	<500	200 - 100k	9.6 k/55.55 k/166.67 k
(Max) data rate - downlink	[bps]	100	EU: 300 - 50 k US: 900 - 100k	1k - 10M	<500	200 - 100k	9.6 k/55.55 k/166.67 k
Max messages/day - uplink	[-]	4	/	?	?	?	?
Max messages/day - downlink	[-]	140	/	?	?	?	?
(Max) packet length - uplink	[bytes]	12	User defined, <256k	>10	20	>10	<256k
(Max) packet size - downlink	[bytes]	8	User defined, <256k	?	20	?	<256k
Encryption	[-]	/	128 AES	128 AES	128 AES	128 AES	128 AES
Battery life - magnitude indication	[-]	10 years	5 years	3 - 5 years	10 years	3 - 8 years	2 - 25 years
Roaming in package?	[Y/N]	Y	N	?	?	?	?

Chapter 4

Decision Tree

As already mention in chapter 1, one of the goals of this paper is to be generic. Therefore, the content does not stop at elaborating the several options (chapter 3), but also guides the reader in the decision making of an arbitrary use case, by means of this series of questions. Its added value is in quantifying the importance of a certain aspect and in the way of approaching a use case, for example: if I know how many end nodes I need, what should I look at next?

4.1 Goal of this approach and remarks

The decision tree contains a series of questions of technical nature. The reader starts at question 1 and depending on the responses, goes through a series of different questions on his use case and its requirements by means of a walkthrough. At the end, a list of networks that are still technically feasible to use can be made, since others will be ruled out of the comparison. Among these feasible networks, some can be considered recommended/preferable over other because of the nature of the application probably gives an economic advantage to their deployments. There are at the end thus 3 lists. One contains the ruled out networks, one contains the leftover possibilities and the last one contains the networks that will possibly be the most cost efficient.

All questions asked are of a technical nature and are a real world interpretation of a at least one parameter presented in the previous chapter.

When starting the walkthrough at question 1, all networks are still included. While navigating through the tree, some networks will be excluded, while others remain. Once a "STOP" is encountered, the user can choose any of the remaining networks to use for his application. When at some point, there are multiple possibilities to answer, both have to be addressed separately and the results should be combined afterwards.

Since some of the asked questions will rule out a network definitively (technical impossibilities), these questions will be marked as "restrictive", meaning that if a certain protocol gets ruled out, it is impossible to add it again to the options list afterwards. The second option for a question classification is called "indicative", meaning that of all the networks that are still feasible, the named networks in that question should be preferred over other (still) feasible options.

A final remark: there is an option available where it is possible to add solutions to a certain question. This is because it is an indicative question, and less frequent real life scenarios can influence the solution options.

4.2 Decision tree

The user should always start with question 1, represented by table 4.1. In home automation applications, the networks focus is on automating a diversity of activities such as starting the coffee machine when your alarm sounds in the morning or turning on the radio when you enter your house. In these cases, Zigbee and Z-Wave are very well suited. However, since they have some drawbacks, such as for example amount of devices and the fact that they don't support mobile applications, which is why you are referred immediately to question 7 d. If you suffer from this drawback, you will have to take another option in question 1, since your list of possible options would be empty when encountering a "STOP".

In case you do require home automation, but should not use Zigbee or Z-Wave because the network would be too big, some programming knowledge is required to enable automation when using other options, in case you effectively want to reach the same level of home automation. As also stated in chapter 3, it is possible to do home automation with any network, and for all networks requires grosso modo the same amount of programming.

A very important note to the reader: it is not because the option reads home automation, that the application has to happen indoors. It is also possible to build the network outdoors, and automate certain activities over there. Furthermore, returning to the tree, if you would require home automation, you no longer should consider using Bluetooth (will not succeed) or satellite (cellular would simply be less costly) since this question is marked "restrictive" and thus once a network is ruled out, it should no longer be considered.

If your IoT related case has the purpose of collecting (large) amounts of data, rather than automating certain activities (which is also possible), the first question to ask is whether or not the service you provide is proximity based. Proximity based aims at: "Can you solve the problem using beacons dispersed over a (possibly large) region, where each beacon offers network connection to the 5-10 metres of their surrounding?". If this is not the case, BLE can be ruled out permanently. Otherwise, a BLE approach will prove to be very efficient. Of course, if both the options are feasible, 2 separate solutions will arise.

Table 4.1: Question 1: Nature of application

Questionnumber	1 - Nature of application			
	Restrictive			
Question	What is the nature of your application?			
Options	Home automation	Data accumulation, triggered events		Wireless connection
Differentiation		Proximity based, eventual advertising	Not proximity based, range required	
Result	Exlude Satellite, Bluetooth	BLE	Exclude Zigbee, Z-Wave, Bluetooth, BLE	Bluetooth
Go to Question	7 d	STOP	2 a	STOP

After specifying the nature of your application, it can be useful in some cases to develop a proper protocol, see table 4.2 . The user might notice that you don't arrive at this question in all cases. The reason here is simple, developing a proper protocol requires a rather large amount of time, estimated at at least one year depending on the size of your team, thus delaying the deployment. Furthermore the only parties interested in this scenario would be large industries, since sometimes they don't want to leave their valuable data in hands of "unknown" protocols. This option is mentioned here as a possibility, but will not be part of the cost analysis.

TABLE 4.2: Question 2: In house protocols

Questionnumber	2 a - In-house protocols	
	Indicative	
Question	Do you have in house knowledge to develop protocol and System on Chip (SoC)?	
Options	Yes	No
Result	/	/
Go to Question	2 b	3 a

Questionnumber	2 b - In-house protocols	
	Indicative	
Question	Team capable of development in a suitable timeframe? (>6 months)	
Options	Yes	No
Result	Consider own protocol	Don't develop own protocol
Go to Question	3 a	3 a

For the following analysis, it is more comfortable to look at questions 3, 4 and 5 at the same time, seen in tables 4.3, 4.4 and 4.5. Some questions might look very similar at first, but when arriving at question 4b for example, the leftover networks will be different than when arriving at question 4a. Therefore, the questions or their options differ slightly but are very similar.

Questions 3, 4 and 5 should be considered together, since requirements such as coverage (4.3), location (4.3), amount of devices (4.4) and their battery lifetime (4.3) all together decide which network to use, rather than one being more important than another. That is also the reason that neither of these questions is restrictive, they should be regarded as guidelines, and they will make a certain network (economically) preferable over another.

The first question in series, table 4.3 handles on the location of the application. Lets clearify a litle on when to select the "overseas" option. When the application is overseas or located in a remote area with no public network options available, you can connect all devices in the area to a central point by using protocols that offer private network options. Of course, when overseas for example, these end nodes are then connected to a central base station, but the station itself is not connected to the outside world. For connection outside of the boat, the user has to search salvation in satellite communications. If this would be the case, you can use any private technology on the boat and the "overseas" option is not really the option you should pick, rather the remote area option is the correct one here, since it is only the base station that is connected over satellite and not the end nodes. In this case, the additional cost of connecting the base station to the satellite network, will not be considered. Since it is a comparison and the cost is the same for each protocol, these costs are not relevant. These costs are the same because you can centralize all data on the boat and then transmit it, which comes down to a transmission of an more or less equal amount of bytes, regardless the protocol and thus results in the same costs. If however, you would want to connect each end node separately to the outside world, satellite communications is required for each of those nodes, and in this case the overseas option is the one to select. It is of course clear that this is a very costly approach that will only be taken if you really want worldwide coverage for your end node, this conclusion also follows from the combination of questions 3, 4 and 5.

Table 4.3: Question 3: Location

Questionnumber	3 a - Location		
	Restrictive		
Question	Location of application?		
Options	Overseas	Land area - remote	Land area
Result	Satellite	Private LPWAN, satellite, WiFi to satellite, (Zigbee, Z-Wave)	No restrictions
Go to Question	STOP, satellite is solution	4 a	3 b

Questionnumber	3 b - Location	
	Restrictive	
Question	Public network available? (Cellular, Sigfox, WiFi)	
Options	Yes, or at least one	No
Result	Exclude Satellite, (Exclude non present network)	WiFi to satellite, Satellite, Private LPWAN, (Zigbee, Z-Wave)
Go to Question	4 a	4 b

Questionnumber	3 c - Coverage		
	Indicative		
Question	What is the required scale of your application?		
Options	(Near) Global/ Continents, Nations, Large industries	Industry scale	Home scale
Result	LPWAN, Cellular	Cellular, LPWAN	No restrictions
Go to Question	6 a	6 a	6 a
Additional question	Is there a freely accessible network already in place?		
Result additional question	Add that network to all options above		

Questionnumber	3 d - Coverage		
	Indicative		
Question	What is the required scale of your application?		
Options	Large industries, nations	Industrie scale	Home scale
Result	LPWAN private, satellite	LPWAN private, satellite	WiFi
Go to Question	7 a	7 a	7 a
Additional question	Is there a freely accessible network already in place?		
Result additional question	Add that network to all options above		

TABLE 4.4: Question 4: Amount of transceivers

Questionnumber	4 a - Amount of transceivers				
	Indicative				
Question	What is the amount of required transceivers?				
Options	<100	>100	>256	>1000	>5000
Result	WiFi, satellite	LPWAN private	Exclude Zigbee	Exclud Z-Wave	Exclude satellite
Go to Question	5 a	5 a	5 a	5 a	5 a

Questionnumber	4 b - Amount of transceivers				
	Indicative				
Question	What is the amount of required transceivers?				
Options	<100	>100	>256	>1000	>5000
Result	WiFi, cellular	LPWAN - public	Exclude Zigbee	Exclude Z-Wave	LPWAN - private
Go to Question	5 b	5 b	5 b	5 b	5 b

TABLE 4.5: Question 5: Lifetime

Questionnumber	5 a -Lifetime		
	Indicative		
Question	Required lifetime and usage intensity of your application? (m = month, d = day)		
Options	3 years, regardless of usage	Intenser or longer than option 3	1 m, 20 m/d or 4 m, 5 m/d
Result	LPWAN	LPWAN if large network	No restrictions
Go to Question	3 c	3 c	3 c

Questionnumber	5 b -Lifetime		
	Indicative		
Question	Required lifetime and usage intensity of your application? (m = month, d = day)		
Options	3 years, regardless of usage	Intenser or longer than option 3	1 m, 20 m/d or 4 m, 5 m/d
Result	LPWAN	LPWAN if large network	No restrictions
Go to Question	3 d	3 d	3 d

The following part, tables 4.6, deals with the technical limitations of the different networks, the questions are very straightforward and they map tables 3.2, 3.3 and 3.1 in a question format. These questions are also restrictive and thus rule out networks permanently since they really handle on what a network is capable of doing.

TABLE 4.6: Quesion 6: Technical

Questionnumber	6 a - Technical	
	Restrictive	
Question	100% arrival certainty required?	
Options	Yes	No
Result	Exclude Sigfox (Weightless-N possibly)	No restrictions
Go to Question	7 a	6 b

Questionnumber	6 b - Technical					
	Restrictive					
Question	# Bytes per message required?					
Options	<12	>12	>20	>64	>256	>1025
Result	No restrictions	Exclude Sigfox	Exclude Weightless - N	Exclude Z-Wave	Exclude Zigbee	Exclude Bluetooth
Go to Question	6 c	7 a	7 a	7 a	7 a	7 a
Additional question	/	/	/	/	/	/
Result additional question	/	/	/	/	/	/

Questionnumber	6 c - Technical	
	Restrictive	
Question	# Uplink/downlink messages/day?	
Options	>140/4	<140/4
Result	Exclude Sigfox (Weightless-N possibly)	No restrictions
Go to Question	7 a	6 d

Questionnumber	6 d - Technical			
	Restrictive			
Question	Required data rate?			
Options	<100 bps	>100 bps	>500 bps	>50 kbps
Result	No restrictions	Exclude Sigfox	Exclude Weightless - N	Exclude LoRa
Go to Question	6 e	7 a	7 a	7 a
Additional question	/			
Result additional question	/			

Questionnumber	6 e - Technical	
	Restrictive	
Question	Real time transmissions required?	
Options	Yes	No
Result	Cellular, WiFi, Satellite	No restrictions
Go to Question	7 a	6 f

Questionnumber	6 f - Technical	
	Restrictive	
Question	Do you want your data to be encrypted?	
Options	Yes	No
Result	Exclude Sigfox	No restrictions
Go to Question	7 a	7 a

In addition to technical limitations of the various protocols, there are restrictions in the extent in which they can handle mobility, which is represented in question 7, 4.7. Remark that these questions as well are restrictive and thus their conclusion is permanent. On the topic of mobility, location accuracy might also be discussed. There is however little information available at this topic. Claims however are that Sigfox can not achieve accuracy but to several 100 metres. Other technologies would be capable of more accurate location determination, up to 1 meter.

TABLE 4.7: Question 7: Mobility

Questionnumber	7 a - Mobility	
	Restrictive	
Question	Is your application moving?	
Options	Yes	No
Result	/	No restrictions
Go to Question	7 b	8 a

Questionnumber	7 b - Mobility	
	Restrictive	
Question	Does a device move out of range of original BS? (Handoff)	
Options	Yes	No
Result	Exclude Zigbee, Z-Wave, Bluetooth	No restrictions
Go to Question	7 c	7 c

Questionnumber	7 c - Mobility			
	Restrictive			
Question	Movement speed of device?			
Options	>200 km/h	>120 km/h	>20 km/h	<20 km/h
Result	3G, 4G, Satellite	Cellular, Satellite	LPWAN, Satellite, Cellular	No restrictions
Go to Question	8 a	8 a	8 a	8 a

Questionnumber	7 d - Mobility	
	Restrictive	
Question	Is your application moving?	
Options	Yes	No
Result	Exclude Zigbee, Z-Wave, Bluetooth	No restrictions
Go to Question	1, try other approach	3 a

Questionnumber	7 e - Mobility	
	Restrictive	
Question	Does a device move out of range of original BS? (Handoff)	
Options	Yes	No
Result	Exclude Zigbee, Z-Wave, Bluetooth	No restrictions
Go to Question	1, try other approach	3 a

The last part handles on "updates over the air", table 4.8. If your application will requires a change in throughout values the course of its lifetime, it is advised you take a protocol which enables this feature. An example would be if you want to send the temperature in Kelvin instead of Celsius. None of the protocols here has this feature enabled, but in for example Sigfox it would be impossible to implement because of the limited data rates and packet sizes. In other protocols, some programming is required to enable this feature.

Table 4.8: Question 8: Updates over the air

Questionnumber	8 a - Updates	
	Restrictive	
Question	Do you require updates over the air?	
Options	Yes	No
Result	/	No restrictions
Go to Question	8 b	STOP
Go to Question	STOP	STOP

Questionnumber	8 b - Updates	
	Restrictive	
Question	Do you have the in-house programming knowledge?	
Options	Yes	No
Result	Outsource, protocols: LoRaWAN, Cellular, WiFi, Satellite	Symphony Link
Go to Question	STOP	STOP

Chapter 5

Life Cycle Cost Comparison

5.1 Introduction

In the previous chapter, results came in the form of lists. The networks on the excluded list are no longer considered in this stage, all other networks are still possible. Furthermore, the networks on the preferred list, for a certain application, are expected to be the most cost efficient in a financial analysis.

Financial comparison of the networks is done by means of a model. A model is only as good as its assumptions. Furthermore, garbage in results in garbage out. Therefore, the correctness of the input is also an important factor. In this chapter, the different features of the model are elaborated, along with its assumptions and non use case related input.

Next to use non use case related input, there is input related to the use case. The latter is to make to (excel) implementation of the model as generic as possible. A non-generic approach would simply present a use case and sum up the different costs for all relevant networks, but here costs of an arbitrary use case can be quantified.

It should be noted that the model does not calculate the total cost for each protocol. Rather it makes a comparison between the different alternatives. Cost categories that invoke major differences in costs, are therefore considered. Cost sources that are of comparable magnitude, are left out.

5.2 Modelling approach

Quantifying the costs is done by adding up the cost pieces of the several costs categories. Cost categories are for example the installation of the base stations. The cost for installation however, is driven by more than one parameter. Examples are the amount of hours it takes to install one station, but as well the travel distance in between two stations and the cost for one hour of personnel. These are all examples of so called cost drivers. Increasing the amount of the cost drivers, increases the total cost amount of that category and vica versa. Estimating the cost for the category "base station installation" thus comes down to identifying and dimensioning its cost drivers.

All possible cost drivers are given, in the sections Capital 5.3.1 and Operational Expenses 5.3.2. Afterwards, these cost drivers are budgeted, in the following sections. The assumptions and calculations for budgeting these drivers are also set forth in these sections.

5.3 Building Blocks of the model

5.3.1 Building Block 1: Capital Expenses - CAPEX

Capital Expenses are the upfront expenditures, they do not recur on any basis. There are different cost drivers that make up the total CAPEX. Some networks will use similar cost drivers, others will need additional ones. All possible cost drivers are presented in table 5.1.

TABLE 5.1: CAPEX - cost categories and their cost drivers

CAPEX			
Cost category	Details	Cost drivers	Secondary cost drivers
Communication chip		Amount of end nodes	
		Cost per end node	Sensor and transceiver chip
Initial battery installation	Installation action	Hours of technical personnel	Amount of end nodes
			Surface of area to cover
			Installation difficulty additions
		Hourly cost of technical personnel	
	Material	Amount of batteries per transceiver	
		Amount of transceivers	
		Cost per battery	
Network installation	Base station purchase	Amount of base stations	Range of basestation
			Surface of area to cover
		Cost per base station	
	Programmers	Amount of months programming	
		Programmer cost per month	
	Repeaters	Amount of repeaters	Surface of area to cover
			Range of repeaters
		Cost price per repeater	

The exact cost of a communication chip (transceiver) can differ over the different protocols, as it accounts for a cost difference it is included in the cost categories. It is a non recurring cost since you only have to buy it once, not considering outages. Buying more chips will increase this categories cost, and therefore is a cost driver. The same goes for the cost of the chip. This category is relevant to all networks.

The network installation category is only relevant to private networks like private WiFi networks and LoRa-private. The different items of network installation can be found in table 5.1.

5.3.2 Building Block 2: Operational Expenses - OPEX

Operational expenses are recurring by definition. From this perspective, the lifetime is always a cost driver, for each category. As this is rather obvious, this driver is omitted in table 5.2. The importance of the required application lifetime cannot be stressed enough. If for example a cellular solution is not competitive on a 10 year scale with LPWAN technologies, this might be very different on a 6 month scale.

Operational Expenses are sometimes discounted. Discounting accounts for the time value of money, where future expenses (as well as revenues, but those are irrelevant in case of a cost comparison) are downgraded by means of a discount factor. The total expenses are derived by formula 5.1.

$$NPV = \sum_{t=1}^{LT} \frac{CF_t}{(1+r)^t} \tag{5.1}$$

TABLE 5.2: OPEX - cost categories and their cost drivers

OPEX			
Cost category	Details	Cost drivers	Secondary cost drivers
Subscription fee		Amount of transceivers	
		Amount of Megabytes exchanges monthly	
Battery replacement	Replacement action	Hours of technical personnel	Amount of end nodes
			Surface of area to cover
			Installation difficulty additions
		Hourly cost of technical personnel	
	Material	Cost of battery	
		Amount of batteries per end node	(possible improvement)
		Amount of transceivers	
Network operation	Location rental	Amount of locations to be rented	
		Cost price per location	
	Maintenance BS	Amount of base stations	
		Hourly cost of technical personnel	
		Amount of hours technical personnel for repair	

Here again, not all cost categories are not relevant for all networks. In private networks for example, subscription fees do not have to be paid.

It can not be stressed enough that all following sections in this chapter are in function of quantifying all items in tables 5.1 and 5.2. The keyword of every section can always be found in one both tables.

5.3.3 Building block 3: User input

The purpose of user input is to create a generic model. Some of the previously presented cost drivers are direct user input, an example is the amount of transceivers which is a cost driver for the cost categories "subscription fee" in OPEX and "communication chip" in CAPEX. Other user input is indirectly related to cost drivers and this is where the assumptions come in, which will be elaborated in the following section.

The possibilities of different input parameters are listed below. Wherever an input parameter is a direct cost driver, this will be emphasised.

- Amount of rural and urban end nodes deployed. This is a direct cost driver.
- Battery lifetime, frequency of replacements, related:
  - Required lifetime of the application. Some clients simply do not require 10 years of connection. This is an implicit cost driver for OPEX.
  - Amount of transmissions and received messages on a daily basis for each transceiver.
  - Amount of characters per transmitted message. Its importance is in the actual transmission time, which has an impact on the battery life.
  - The compression factor. The factor is the amount of messages combined in a single transmission. If the use case requires alarming messages, indicating that personnel attention advisded, this approach is not feasible and the factor should be 1. The factor is only applied to cellular, satellite and WiFi.
  - Number of updates over the air on a monthly/yearly basis. The battery lifetime drops, since the receive frame of the end node has to be open, therefore consuming more energy. Since none of the protocols offer this feature in their package, its addition is considered a possible improvement for future research.
- Battery replacement (physical action) related:
  - Difficulty of replacement: low/medium/high/ultra. This part only refers to the physical action of replacement, when the person is standing on the location of the end node, and has no link with the distance that the personnel has to travel or whatsoever. For example replacing a battery of a device that is mounted to the wall on eye level would be classified as easy. If the sensor is no longer mounted at eye level, a medium level is advised. Replacing a battery inside a buoy at sea would be classified as high, whilst replacement of a battery on a high voltage power cable, which typically also requires a platform worker due to its altitude, would be considered an ultra scenario.

Some sound judgement is required for this parameter. In section 5.3.6.1 , it will become obvious how this parameter has a rather large influence on the result, so frivolity is discouraged. As the number of sensor devices deployed increases, the importance of this parameter grows.

  - Required actions for battery replacement. Digging sand, digging concrete, positioning and climbing a ladder can be activated if relevant. Also, a direct second wise addition for each sensor device during battery replacement can be budgeted. A time study for the action under consideration is advised when calculating an extraordinary time addition. The amount of seconds added for the aforementioned actions are listed in table 5.3.
  - Enabling or disabling the following 3 options. In the battery replacement cycle of the personnel, as will be elaborated further, there are 3 stages. First they have to travel to each end node one by one, next they change the battery of the end node and finally it is possible that the end node is mounted on a special place, such that additional (extraordinary) actions are required. Each of these 3 stages can be enabled for each protocol. Why is this useful? For example, if because of the context of the use case, end nodes are only 1 week in the field and are then recovered before being reused, then the travel requirement can be disabled, since the nodes have to be recovered anyway, regardless of the used protocol. The battery exchange (with or without extraordinary additions) however still has to take place, on a different time basis for each protocol.

- Coverage related
  - Urban and/or rural surface of the area. Increasing the covered area, increases the distance that technical personnel has to travel during battery replacements.
  - The amount of buildings and amount of range extenders per building. For some technologies this is important, in order to be competetive on the aspect of indoor penetration. Those extender are placed on the inside of the outer walls and retransmit the signal. Since they have to be always on, these should be wired. The extenders thus enhance the received signal strength by simply repeating the transmissions. It can be used for all options, except Sigfox,

since they don't offer it. Sigfox however, has no need for it since its indoor penetration ranges to 20 metres below the ground.

  - The amount of repeaters. This is not the same as the foregoing, since in this case it simply aims at extending the range of the network, rather than enhancing the singal strength indoors. This option is available for WiFi, Zigbee and Z-Wave. This way they can cover a larger area with only a single base station.

- Installation requirements

  - In some use cases it is possible that a specific network is already deployed in that region and is free the use for anyone. Therefore network installation can be enabled and disabled, as to fit the real life situation. There is a similar on-off possibility for subscription fees.
  - Additional time addition per installation of base station. This can be different for each technology.

TABLE 5.3: Secondwise addition per transceiver for frequently required actions in battery replacement

Time addition [s]	
Ladder	15
Digging sand	30
Digging concrete	1500

5.3.4 Building Block 4: Fixed economic input and assumptions

The previous input was all rather use case related. In addition there are some fixed values, moreover cost information. Some of those are technical, others are economic cost information. Some of these values, either technical or economic, can be estimated with high certainty, others can not. Those that are uncertain, require assumptions and will be referred to as such. For the model to work, these assumptions need an initial value. The impact of these uncertain parameters is measured by a sensitivity analysis in chapter 7.

All economic input values are, thus as well initial values for assumed parameters, listed in table 5.4 and their origins are explained over the course of this chapter. The technical fixed parameters are highlighted in section 5.3.5.

TABLE 5.4: Cost prices and assumptions

Parameter	Details	Time basis	€
Technical personnel		Hour	75
Programming personnel		Month	5000
Location	Owned	Month	25
	Rented	Month	75
Sensor and Arduino	Addition to chip	-	25
Data storage		Month	Neglegible
Battery	Lithium Ion	-	1,43

The location rental is not applied to WiFi. The €25 for owned locations originates from €15 for WiFi connection of the base station (which would be counted double here) and €10 for electricity and routers do not consume this much power. Furthermore, the €50 difference with rented locations completely goes into rental and maintenance of the base station. This would be a very high add-on, and one can easily find locations where the placement would be cost free. Its maintenance also is limited in cost, since these devices are highly reliable.

There are also network related cost prices, those are listed in table 5.5. For some of the protocols, pricings are unknown and are indicated with a question mark. Subscription fee information to the public networks is to be found in appendix B.

TABLE 5.5: Costprices of different network elements for all protocols

Element	Transceiver		Base station/Router/Coordinator		Extender/Repeater	
Network	Name (example)	€	Name	€	Name	€
Sigfox	CC1120	2,15	-	-	-	-
LoRa	SX 1272	5,4	LL-BST-24	4000	-	-
Weightless	NW1000	?	Nwave gateway 1000	?	?	?
Cellular	WTR3925	7	-	-	SCS-2U01	219,22
Satellite	Iridium 9602	200	-	-	?	?
WiFi	ESP8266	6,95	D-LINK DIR-809	39,99	D-Link AC1200	46,28
BLE	CC2540	4,45	iBeacon 2 BLE	29,99	-	-
Zigbee	CC2520	>5	RG4100	83,45	CC2520	4,15
Z-Wave	Aetoc	>25	Zipato ZipaMini	107,05	?	4,15?

A last important notion on the topic of cost prices is economies of scale. When buying larger amounts from a certain item, it is fair to assume that the buyer will receive a discount, which is in literature referred to as economies of scale. On all purchased items, regardless of the technology, a discount is applied depending on the amount. For 100 items, 90% of the original price is charged. When purchasing over 10000 items, this drops further to 81% of the original price. It is possible extend this in a linear fashion, but in reality discount are also often offered in a staged way. The exact values here are allocated rather randomly, although realistic. Since ”correct” values of the percentages are hard to estimate, this is an ideal input for the sensitivity analysis.

5.3.5 Technical information

There are some technical parameters that are invariable and used in further calculations, which is the next section. Here again as with the economic input, some values are straightforward, others should be more or less estimated. The latter ones again can be subjected to a sensitivity analysis afterwards.

Table 5.6 shows all the values. Some of this input will prove unnecessary to obtain results, but they are presented all the same.

TABLE 5.6: Technical input values

Technical parameters	Range around BS		Users/BS	Datarate	Max packet size	Uplink/Downlink
	Outdoor/Rural	Indoor/Urban				
Protocol	[m]		[-]	[bps]	[bytes]	[Messages/day]
Sigfox	50k	5k	1M	100	12	140/4
LoRa	10k	3k	65k	50k	256	NI
Weightless - nWave	?	?	?	<500	52	?
Cellular - 2G	Unknown, NI			?	Large, NI	Unlimited
Cellular - 3G				>1M		
Cellular - 4G				>1M		
Satellite				>1M		
WiFi	100	50	253	>1M		
Bluetooth	100	10	8	>1M		
BLE	80	10	?	1M		
Zigbee	75	75	256	250k	133	
zWave	75	75	256?	100k	64	
Note	NI = Not important for this paper					
	k = 1000; M = 1000000			k = kilo ; M = Mega ; G = Giga		

5.3.6 Building Block 5: Calculations

From the previous building blocks, it is now possible to quantify the remaining cost drivers that are not directly user input. The exact input values for these formulas/approximations have already been presented in the previous sections. Thus if the reader wants to check on the results of the use cases in chapter 6, the necessary values can just be plugged in here.

5.3.6.1 Calculation 1: Technical personnel

Technical Personnel is a cost driver for the categories "Battery replacement (OPEX)", "Maintenance base station (OPEX)", "initial battery installation (CAPEX)" and "Network installation (CAPEX)", as can be seen in tables 5.1 and 5.2 . The cost of technical personnel is always €75 per hour, see table 5.4, regardless of the activity. The amount of hours, also a cost driver, will be specified here.

The amount of hours for "Network installation" is logically only relevant to private network options. This embraces the wiring of repeaters/range extenders, the installation of base stations, the travel time between 2 repeaters/range extenders or base stations, the eventual programming to enable meshing between 2 base stations and the monthly cost of a programmer (different from technical personnel). All assumed values on the topic of network installation are presented in table 5.7, except for the travel time between base stations. The travel time is estimated using a formula, similar to the one used later in this section under "Technical Personnel: Network density component". The values in table 5.7 are obtained from industry experts, since data is not available on those. Others are estimated and can be subjected to the sensitivity analysis afterwards.

TABLE 5.7: Network installation details

Network installation	BS installation	Repeater/Extender
Action	All actions	Attach and wire
	[hours]	[hours]
LoRa - Private	2	0,5
Weightless - nWave	?	0,5
WiFi	0,5	0,5
BLE	0,2	/
Zigbee	1	0,5
Z-Wave	1	0,5

Handling on the next cost driver, "Maintenance base station" also includes a certain amount of hours technical personnel. It should be clear that also this cost is only relevant to private network options. The amount of hours required is difficult to estimate since it depends on the exact defect that occurred to the base station. Furthermore, estimating the frequency of this outage is very difficult and data is not obtained (companies usually don't publish the downsides of their offers). Because it is so difficult to estimate, but non the less is expected to have a significant impact on the comparison, there are some assumptions required. The approach of estimating the amount of hours is abandoned and replaced by an additional cost. For each base station, a monthly fee of €25 has to be paid, for maintenance. If the base station is installed on a rented location, the monthly fee will be €75, thus including a €50 rental fee. The €25 thus translates into a monthly check of technical personnel, to see if the base station is still functional, if not, additional costs are also included in this €25 fee. Again, the significance of the impact of this parameter is is tested by means of a sensitivity analysis.

The next technical personnel related cost driver, "battery replacements" (and initial deployment) of the sensor devices in the field have to be carried out. The "initial deployment" is the same cost, but only occurs once. The calculation is broken down in 3 parts here. The travel time between the end nodes in section "Technical Personnel: Network density component", the actual action of replacing a single battery in section "Technical Personnel: Battery handling component" and finally a user specified extraordinary time addition per end node in section "Technical Personnel: Additional factor component". Recall that the formula in section "Technical Personnel: Network density component" is the same that is also used for calculating the travel time between base stations when installing them.

- Technical Personnel: Network density component

The first segment is network density based. Network density is the amount of devices per km^2. The higher the density of the network equivalently, the closer the sensors are spaced together, the less the operator has to travel from one sensor to another. The total time the operator spends travelling is thus the distance between 2 sensors multiplied by the number of sensors minus 1. Formula 5.2 gives the distance between 2 sensors in (for example) an urban environment (the same formula goes for rural applications and in case both are present their values are simply added up).

$$Distance = \frac{\sqrt{\text{Surface of area}_{urban}}}{\sqrt{\text{amount of sensors}_{urban}} - 1} \tag{5.2}$$

The reasoning behind formula 5.2 is based on the travel scheme in figure 5.1. The amount of nodes on a single side is the square root and the distance on one side (thus the length of one side of the square) is the square root of the area.

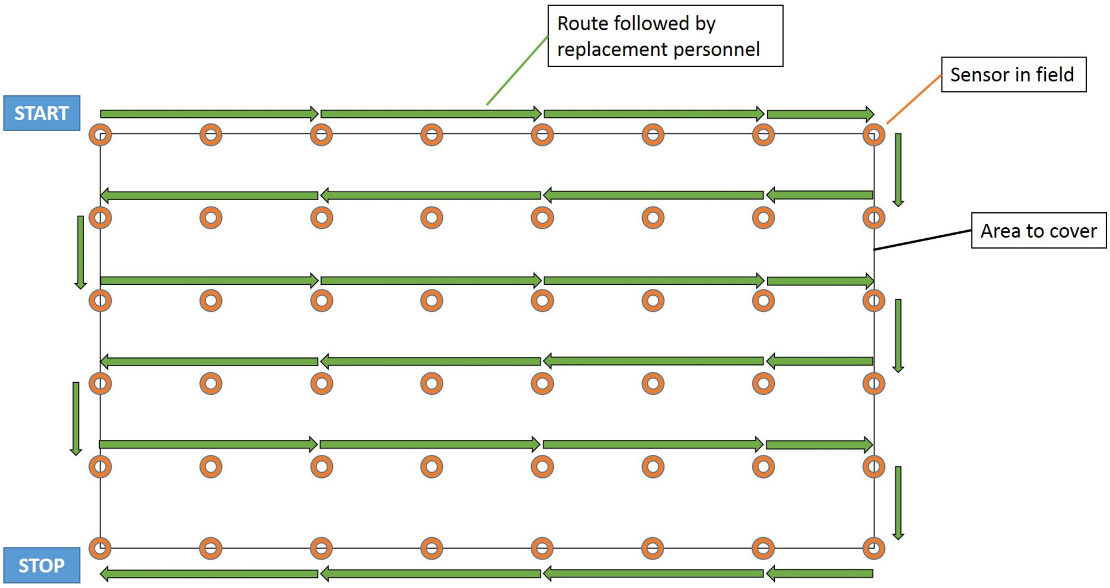

FIGURE 5.1: Assumed travelroute for battery replacement

Once the total distance is known, the time an operator spends travelling is then estimated by dividing the total distance by his travel speed. Of course, the travel speed depends on the distance to be travelled between two sensors, as when the total distance exceeds a certain threshold, the operator will use a vehicle for transportation. Table 5.8 represents the assumed travel speeds in function of the distance.

TABLE 5.8: Relation between travelspeed and distance to travel

Distance		[m]	<20	<100	<1000	>1000
Travelspeed	Rural	[km/h]	4	5	50	90
	Urban		4	5	30	120

For small distances the operator will not reach a faster pace, while travelling by foot. From a threshold of 20 meters he will reach this higher speed. When the travel distance exceeds 100 meters, he will use a means of transport like a car and his travel speed increases. When the distance exceeds 1 kilometre, he will be able to use roads allowing higher speeds, again enabling higher speeds. Of course, the speed of a vehicle differs from urban to rural areas.

Possible improvement: allow the user to decide whether the devices are collocated in hubs rather than uniformly spread. Each hub then contains an amount of the sensors, and is characterised by its diameter. The spacing between the different hubs would be uniform. This also implies that the base stations would not have to fully cover an area, but only the spots where hubs are located. This now is possible by inputting the different hubs separately and adding up the costs and its added value is thus limited.

- Technical Personnel: Battery handling component

Replacement time of one single battery, once the battery is only a few centimetres removed from the body can be estimated using a time study. If a single transceiver uses more than a single battery, the time of replacing a battery is multiplied by the amount of batteries. The time study is roughly the same for most of the batteries, except for the car battery, due to its drastically different dimensions and weight. Car batteries are however not considered in this paper. Batteries are lithium ion ones, because of their high capacity of 12000 mAh.

Time studies typically include a working pace. This is similar to learning curves, since they represent the same idea: an operator performing a series of actions once, will not achieve the same speed as an operator performing this series of actions for a certain amount of times.

Working paces are expressed in the unit Bedaux. 60 Bedaux is considered the industry standard working pace for an experienced, normal health operator. The thresholds in this case are set on the hours the operator performs the series of actions, and presented in table 5.9.

TABLE 5.9: Acquired Bedaux level in function of worked hours

Hours of replacement	<30	<150	<500	>500
Bedaux	40	50	60	70

The time for replacing on battery is expressed in Time Measurement Unit (TMU), when using time studies. One TMU equals 36 milliseconds, at 60 Bedaux, the industrial working pace. At different levels of Bedaux, you multiply 36 milliseconds by that factor and devide by 60.

Table 5.10 summarizes the required actions and their TMU magnitudes for replacing a single, standard sized battery. The information for building this time study is available in [9].

Table 5.10: Time study for a battery replacement

Action	Motion	TMU	Explanation motion
	Reach	36,4	Move hand to battery on table
	Apply pressure	10,6	To be able to get empty battery out of holder
	Disengage	11,8	Battery recoils when getting out of holder
	Grasp	10,8	Get battery out of holder
	Regrasp	5,6	Regrasp battery to get firm hold
	Move	21,8	Move empty battery to pocket
	Reach	29,2	Reach to pocket with full batteries
Replace 1 battery	Release	2	Release the empty battery into pocket
	Reach	29,2	Go with empty hand to pocket with full batteries
	Grasp	10,8	Grasp full battery
	Regrasp	5,6	Regrasp for firm hold
	Move	15,1	Move full battery
	Apply pressure	10,6	To be able to get full battery in holder
	Position	19,2	Get full battery in holder
	Release	2	Release hold of battery
Total 1 battery		220,7	
	Reach	36,4	One hand to sensor
	Grasp	2	Get hold of sensor
	Reach	36,4	Other hand to screw driver
Remove cover plate: part 1	Grasp	2	Get hold of screw driver
	Move	15,1	Screw driver to sensor
Get out 1 screw of cover plate	Turn	9,4	Loosen screw with screw driver
	Move	15,1	To put down screw driver
	Reach	29,2	Move hand to get screw out
	Grasp	2	Get hold of loose screw
	Move	15,1	Put screw on table
Part 1: Total for 2 screws		325,4	Remove screws
Part 1 : Total for 2 screws		325,4	Put screws back on
Remove cover plate: part 2	Reach	36,4	Move hand to plate
	Grasp	2	Get hold of cover plate
Remove cover plate	Move	15,1	Put plate on table
Part 2: Total cover plate		53.5	Remove cover plate
Part 2: Total cover plate		53.5	Put cover plate back on
Total without battery		757.8	

The subsequent steps come down to the basic hand motions in removing a battery from a the sensor device, reaching for a battery in a nearby pocket, and placing the battery inside the holder. Of course the results are now in TMU, the results in seconds are summarized in the table 5.11. The line in orange indicates that it would take 35.226 seconds to replace one battery, if no learning effect was used.

TABLE 5.11: Battery replacement times in seconds

		Replacing battery	Cover plate	Total	
				1 battery assumed	Level reached at ... hours
TMU		220,7	757,8	978,5	
Seconds	At 40 Bedaux	11,9178	40,9212	52,839	0
	At 50 Bedaux	9,53424	32,73696	42,2712	30
	At 60 Bedaux	7,9452	27,2808	35,226	150
	At 70 Bedaux	6,810171429	23,38354286	30,19371429	500

Possible improvement: if a large network needs the batteries of its end nodes changed fast, the amount of workers increases and the learning effect slows down since the experience is divided over several persons.

- Technical Personnel: Additional factor component

This major reason this component is included because it is impossible to include all scenarios in a single model. There always will be actions that can not be modelled by the means available here. If this is a small addition per single replacement, up until say 5 seconds, the cumulative effect still will be rather small if not negligible. If more than 5 seconds however, the total cost estimation may be false. For these cases, a user can input a time addition that will be added to each single battery replacement.

As already mentioned before, some more common scenarios like fetching, setting up and climbing a ladder, digging up sensors from the sand or concrete (for example smart parking) are included in the model already and can be activated, see again table 5.3 for the corresponding time additions. Furthermore if the travel speed exceeds 30 kilometres an hour, an additional 10 seconds is included for leaving the vehicle. Additionally, a standard fee of 2 seconds is added for positioning the body, as well as a 3 seconds fee for searching the exact location of the sensor device.

5.3.6.2 Amount of base stations

In private networks, the deployment of the network is a cost to take into account. The prices of those base stations and routers have already been presented previously, but the amount of them required is the topic of this section.

The area covered around a single base station is circular. Since each base station, for a certain protocol/network, has the same range, the question comes down to: How many circles with constant radius do you need to cover a surface? A rectangular area is assumed.

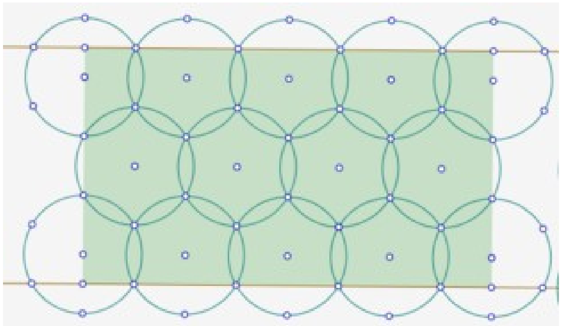

FIGURE 5.2: Hexagonal coverage of a rectangle area [10]

In above hexagonal packing, the amount of circles (thus base stations) for a full coverage of the rectangle amounts: [10]

$$\text{Number of BS} = \frac{2AB}{3R^2\sqrt{3}} \tag{5.3}$$

The origins of equation 5.3 can be found in appendix A.

In equation 5.3, A and B are the dimensions of the rectangle and R the radius of the circle. Note that A and B are use case dependent and R is the range around the base station, which can be found in table 5.5. Furthermore the range of a base station, R, varies from rural to urban areas. Thus when A and B represent urban/rural values, the respective value of R is selected. When there is both a rural and an urban site of the use case, the formula can be applied twice, each time selecting the appropriate R and the total amount of base stations follows from addition of the urban ones to the rural ones.

For most use cases, equation 5.3 will give the amount of base stations. However, as can also be seen in table 5.5, there is a restriction on the amount of users per base stations, this is the amount of transceivers connecting to it. It should be clear that this is only an issue in the case of private networks, since otherwise the provider of the network should foresee a sufficient amount of base stations. Mathematically, this restriction is very easily implemented equation 5.4.

$$\text{Minimum Number of BS} = \frac{\text{Rural end nodes}}{\text{End nodes per BS}} + \frac{\text{Urban end nodes}}{\text{End nodes per BS}} \tag{5.4}$$

Possible improvement: as stated before, the range of base stations now is considered an invariable input. If this could be linked to output powers and sensitivities of transceiver chips, a more correct estimation would be possible. Lack of data however hinders doing so.

Related to the previous improvement note, an enhancement is possible when examining the density of the Sigfox network. In France they installed 1250 base stations over a surface of 643801 km^2, in Belgium however they installed 300 base stations to cover a surface of only 30528 km. The ratio of the Belgian network density (amount of base stations over surface) to the French one is close to 5. The reason is simple, in Belgium Sigfox wants to achieve coverage up till the level of basements. Translated into one of the parameters of this paper: enhanced indoor penetration. This ratio is thus implemented into the model, and the option of selecting enhanced indoor penetration is available, multiplying the amount of base stations by 5.

From the data in the previous paragraph, we can also make an initial check on equation 5.3: does the number of base stations following from the equation, correspond to the number of base stations that Sigfox has installed in France?

$$\text{Number of BS} = \frac{2 * 643801 km^2}{3 * \sqrt{3} * (10km)^2} = 2478 \tag{5.5}$$

The range of 10 kilometres is for a LoRa rural situation. Sigfox achieves higher ranges (50 kilometres) in open field compared to LoRa, which explains the factor 2 difference. The factor should not be 1,5 since there also are cities in France, where the range of Sigfox and LoRa is very comparable.

5.3.6.3 Estimating lifetimes: consumption and reference approach

The aim of this section is to quantify the recurrence of battery replacements. The method that is presented here, is very promising since it gives correct results when compared to online references. This method will be applied to the Sigfox protocol, for estimating the lifetime of its end nodes. For the other protocols, lack of input data for the method is a problem because it often is company secret.

For these remaining networks, the lifetime is simply based on the Sigfox one. For example, the lifetime of cellular is a factor lower than the Sigfox one and WiFi is 2.5 times better than the cellular one. For these ratios, online references are used as well as industry experts advice. [11] [12]

The factor for cellular to LPWAN (or Sigfox) requires some more detail. When the amount of messages is low, the ratio will be around 5 (LPWAN consumes 5 times less than cellular options). When the amount of messages is high however, the ratio becomes 40.

Why is there a different lifetime ratio depending on the messaging frequency? This is because when the amount of messages is low, it is possible to run a power optimisation program on the CPU, reducing the battery consumption of cellular. When the amount of messages is high, this optimisation is no longer as effective, and the factor becomes 40. The optimisation in practice comes down to enabling sleep modes on the cellular end node. In sleep mode the consumption is comparable to LPWAN end nodes. For cellular end nodes to connect to the network however, they require a ton of energy, much more than LPWAN. Therefore, you want to reduce the amount of times the end node connects to the cellular network. When the amount of messages is high, this becomes difficult for the optimisation program. If a message is to be sent every 15 minutes, it no longer is useful to enter these power saving sleep modes, since the end node would consume more by waking up and connecting to the network again than to remain active for 15 more minutes. Since most of the time, these sleep modes are no longer "accessible", the ratio becomes 40.

LPWAN end nodes do not suffer from this issue. They do not consume much energy (if any) in connecting with the network, therefore they can always enter sleep mode. Remark that this is one of the key benefits of these LPWANs.

Table 5.12 summarizes the ratios. The compression factor is also included. Recall that compression is about whether or not messages are stored temporarily, and send in bundles. In table 5.12, a compression factor of 5 is supposed for cellular, WiFi and satellite options. Other factors are of course also possible, however this is more or less user input. Practical values of the compression factor are estimated from 5 to 20. Of course, when the amount of messages is low, their practical function in the use case probably is to alarm, which requires immediate sending, furthermore they can maximum compress 10 messages in one and therefore it is indicated as ”merely possible”in table 5.12.

Table 5.12: Lifetime ratios compared to Sigfox for different protocols

Lifetime compared to Sigfox			
	Messages/day	Before compression	Compression factor?
LoRa	Irrelevant	1	
Cellular	Low (<10)	5	Merely possible
	Moderate (<30)	20	Possible
	High (>30)	40	
Satellite	Low (<10)	5	Merely possible
	Moderate (<30)	20	Possible
	High (>30)	40	
WiFi	Low (<10)	1,71	Merely possible
	Moderate (<30)	6,86	Possible
	High (>30)	13,71	
BLE	Irrelevant	1	
Zigbee	Irrelevant	1	
zWave	Irrelevant	1	

A good question to ask now would be ”Why not simply enter the lifetime for all the technologies, instead of coupling them to the Sigfox lifetime?”. Certainly as these magnitudes of these lifetimes can indeed be easily found online and examples have already been given in table 3.1 for example. The reason this approach is rejected is exactly because it only are magnitudes, like for example ”weeks”, which still is not very accurate because 2 weeks versus 8 weeks could result in a very different outcome (replacement costs times 4). Furthermore, with the method presented here, there also is the advantage that the intensity of usage (amount of messages) is accounted for.

The next part of this section handles on how this lifetime of Sigfox is calculated, in function of the amount of messages.

The consumption rate of end node devices depends on 2 factors. First of all there are the consumption characteristics during transmission, receiving, sleep mode and network pairing/device wake-up, all of which expressed in milli-Amps. Secondly, the time spent in these modes is important. Since consumption characteristics emanate from data-sheet and thus are invariable, a correct approximation comes down to estimates of the durations in each mode. The time needed for network pairing and device wake-up also follow from transceiver data-sheets.

Each duration is calculated on a daily basis. The calculation principle for both transmitting and receiving time is the same. Both are calculated from equation 5.6:

$$\text{time} = \frac{\text{payload data packet}}{\text{bitrate}} * \text{amount of messages per day} \tag{5.6}$$

The amount of messages is the amount transmitted/received, regarding the calculation. The bit rate can be different between up- and down-link transmissions.

The time that the transceiver spends in sleep mode can then be calculated by 5.7.

$$\text{sleep time} = 1\text{ day} - \text{time } T_x - \text{time } R_x - \text{time network pairing} \tag{5.7}$$

As already stated, this method will only be applied to the Sigfox network. The time spent in each state depends on the messaging frequency, thus the use case. The time to transmit and receive messages is calculated in table 5.13 using equation 5.6, for 1 message per day. The time spent in other states is available from data sheets. In table 5.6, there is stated "Await previous message?", where yes is stated. This comes down to the fact that Sigfox transmits messages 3 times, and their bitrate is limited. For this reason, after transmitting for example the message the first time, they have to wait that same amount of time before transmitting that message a second time. Because at the base station side of the network, the message can only be received at the same bitrate, and the reception channel is thus already in use. This information is not available, but assumed by the author. Furthermore, the time to transmit that message 3 times is more or less 6 seconds, which is what Sigfox publishes on their website. Recall that the impact of this approach on this paper is that a correct intensity based approach is obtained, which the magnitude approach does not offer.

Table 5.13: Sigfox, time to transmit/receive 1 message

Payload of message	[bits]	96
Transmission speed	[bps]	100
Await previous message?	[Yes/No]	Yes
Times message transmitted	[-]	3
Time for 1 transmission/reception	[s]	5,76

All time related information is now available. Table 5.14 combines all this information with the electric characteristics. The current consumption characteristics originate from the data sheet or the corresponding device. [13] After plugging in the amount of messages, the user obtains the lifetime for Sigfox, and table 5.12 is used for calculating the lifetimes of the other protocols.

Table 5.14: Lifetime calculation input for Sigfox

Sigfox: CC1125		State			
		Active		Wake up	Sleep
		Tx	Rx		
Time spent in state/day	[s]	5,76	5,76	0,0005	1 day - 5,76*(messages Tx+messages Rx)
Current consumption	[mA]/s	37	13,4	3,63	0,0003
Note		Should be factored by amount of messages			

5.3.7 Amount of bytes exchanged yearly

Some data its value comes from accumulating large amounts, and running analyses on them afterwards. They thus have to be stored. By paying the Sigfox subscription free for example, access to this data comes with the package, moreover this service is included in the subscription fee. In other cases, the storage of this data has to be paid for. Looking up cost values for data storage with for example Amazon [14], the conclusion is that these costs are several orders of magnitudes smaller than all other costs, and thus are negligible. These will thus not be included in the comparison.

5.4 Iterations - Macro

This section is solely included because of a previous approach that did not work because of lack of data, but can be a future improvement. One might argue that the results of the paper would benefit from including more than one end node transceiver chip, since now only 1 example is included for each protocol. This is true, the results would benefit.

At first, several chips were available and included for each network. As were there different types of batteries. A macro in Excel would combine each chip, with each possible battery and select the most cost efficient approach, taking into account the total cost for that network. There are 2 reasons why this is abandoned. The first is a lack of data. As already stated, some characteristics are business secret and thus not available, which hindered in using this method. The second one is the sensitivity analysis, which is also based on an excel macro. It is not possible to let that macro call upon the macro used for this chip-wise optimization, since the author do not have access to the code. This would thus disable the optimization and lead to errornous results.

Of course it is possible to again include this in future research, since the macro is still available in the Excel, it is simply not used.

Chapter 6

Use Cases

In this chapter, some examples are given how all information comes together and what the leverage and implications are of some practicalities in a decision process. The first use case handles on smart containers in the port of Antwerp, the second one on the transport of medication on the level of nations and the last one on the service level of De Lijn, a Belgian public transport company.

An important note, concerning all use cases, is the definition and formulation of the exact needs, as well as some assumptions on their needs since no exact data is available.

6.1 Use case 1: : Smart containers at the port of Antwerp

The port of Antwerp wants to improve their operations by using smart containers. With these smart containers they want to measure a variety of values. They want to know their exact location, as well as safeguard them against burglary by denying access to unauthorized persons. In addition to location determination and safety related features, those smart containers have to measure variables such as acceleration, oxygen contents, temperature, humidity and the possible presence of certain gasses. In total they want to connect 200 000 thousand devices continually.

The port of Antwerp, see figure 6.1, covers an area of 120.68 km^2, making it larger than an home environment, however too large to be considered an industrial site and too small to be considered a small nation.

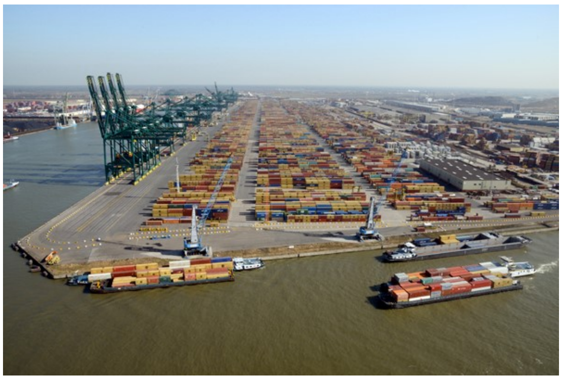

FIGURE 6.1: Port of Antwerp

As already said, the port of Antwerp covers an area of 120.68 km^2. Furthermore, from a LPWAN and cellular point of view, it can be considered as a rural area, since the base station can be placed on an altitude (a tower or high building for example). There will of course be interference, but given the application is still above the ground, sub-GHz frequency signals will only be slightly hindered due to their enhanced indoor penetration.

LAN networks have less range, and as these signals (for some technologies) are supra-GHz, interference will be worse. Furthermore, because of its limited range compared to WAN networks, their base stations are more closely spaced together. The port of Antwerp is an industrial site and a harsh environment for routers/(base stations). Deploying these routers in the field without any protection would leave them broken in short notice. Since high buildings are not present every 200 metres, they should be mounted on a pole, to protect them from daily operations. This pole costs are €200 [15], and its installation would take around 4 hours of technical personnel. They have to bring the pole to its correct position and drill holes for example.

6.1.1 Requirements

- They need to connect a large number of end devices and store their data over a moderate to large area.
- Real time transmission is no requirement. For the burglary issue, devices can wake up as soon as the doors open and ask for the presence of a certain badge. The devices can sleep between those intervals, as well as between the intervals of regular transmission of data (parameter values such as temperature).

- Furthermore, on the topic of messaging frequency, there are two different scenarios. In a first the case, the port wants to connect the devices in order to accumulate all measured data, presumably for further processing. In this case, frequent messages are a key parameter, that will have an impact because of lifetime requirements. In a second approach, a telemetric one, the purpose of connection is to alarm personnel in case of irregularities. It should be clear that the amount of transmissions will drop severely.

- The application lifetime is unclear, but it is assumed that containers will only be in the port during a transit time, e.g. a week or less for most of the products. Containers are equipped with an end node as soon as they enter the port. After leaving the port, the end nodes are recovered and stored, to be used again upon arrival of a new batch of containers. Since end nodes are reused, the application lifetime is set to 10 years. However, from a cost comparison point of view, there is an interesting implication. Each end node is recovered after maximum one week in the field, no matter its lifetime. When changing batteries, it is thus most efficient to replace them whilst the end nodes are already in storage, which eliminates the transport costs. The frequency of replacing batteries however, will account for a cost difference between the different networks.

- The containers are possibly moving/moved during their stay at the port. The speeds during this transport will be moderate, seen the weight of the containers and possibly valuable content, also safety reasons are a factor here. Accuracy in locating the containers requires triangulation, alledgedly this can not be offered by Sigfox.

- Encryption of data might be useful, since it involves industrial materials and the owners of container content will possibly ask for data integrity.

- Especially on the burglary aspect, it is required that messages arrive with certainty. Furthermore the presence of certain gasses is very important since some of them show explosive behaviour etc.

- Updates over the air or not relevant since the devices can be recovered after a short time in the field and updates can thus be applied to the end nodes upon storage.

6.1.2 Decision Tree

Mapping the requirements on the decision tree will recommend several networks.

- Question 1 always is the starting point and the nature of the application here is data accumulation. It is true that some values of data can trigger certain events, think of the burglary aspect where an alarm sound would be appropriate, but that does not influence the decision. It should be clear that an approach where higher ranges are available are more efficient, because of the surface of the area. This excludes the networks Zigbee, Z-Wave, BLE and Bluetooth permanently and leads to question 2a.
- Question 2a will only keep open the opportunity of a self-made protocol, in which we will not go into depth in the framework of this master dissertation, after which continuing to question 3a.
- The port of Antwerp is considered a non remote land area, since there are public networks present. Question 3b is the next question and asks for which public networks are available, others get ruled out. Sigfox can be added to the excluded list at this point, which leads to question 4b. However, because it is plausible that Sigfox will be deployed in the port of Antwerp in the near future, this option will be left open on the condition that the network is present.
- The amount of transceivers is 200 000. Here LPWAN-private (LoRa-private in the current market situation) is advised. This is logical since the rather large amount of transceivers makes LPWAN preferable, but the public LPWANs (Sigfox, Weightless?) are not deployed, which leaves only the private option.
- In question 5b, a straightforward answer cannot be given since the lifetime is not specified. Anyhow, the longer the required lifetime, the stronger the inclination towards LPWAN instead of cellular of WiFi approaches. Because transportation should no longer be considered when replacing batteries, WiFi might actually still be a cost efficient approach. The next question is 3c.
- In 3c the industry scale advises on using LPWANs or cellular approaches. However, since free WiFi network is available at the port of Antwerp, a WiFi approach might as well do the job. However, the downside on the WiFi network available is that

it only covers a fraction of the total port and grants access for only 1 day, as is custom in the port. Furthermore, the available WiFi network serves visiting clients, not their IoT applications. A new WiFi network thus has to be built for this application. Next is question 6a.

- None of the question in part 6 are relevant, since Sigfox is already excluded and other questions are not restrictive to the remaining networks. However, if Sigfox were present (plausible in the near future), a point of interest would be the combination of questions 6b and 6c. Let's go through a practical implementation. If the goal of the end nodes is merely to trigger an alarm, thus telemetric, the amount of bytes is sufficient. The data format would be for example: 3 - 30. The first digit indicates which value is measured, let's say 3 stand for oxygen content. The second information piece then indicates the level, in this case 30 would for example stand for 30%. Thus, Sigfox, would be applicable.

- However, in a different use case, where the goal of the end nodes is to collect data, the amount of messages comes into play. Usually Sigfox is very well suited for collecting data, but the problem here would be the amount of parameters that have to be measured. Lets say 3 parameters can be transmitted in a single message by means of the foregoing data format. Since there are 8 parameters (oxygen content, temperature, ...), the amount of messages for 1 data update would be 3. Sigfox has 140 messages per day available, thus it can update all information 46 times (140/3).

- the next question addressed is 7a. The application is possibly moving, thus leading to question 7b. Handoff might be required, thus excluding networks that were no longer considered anyways. The movement speed of the devices, in question 7c, is rather low, thus the ¿ 20 km/h restriction is sufficient, not granting additional information. This leads to the final question 8, which is not relevant since updates over the air or not required, because they can be applied during storage.

All the foregoing can be summarized by the list of excluded networks, and that one of preferred networks. The excluded networks are Zigbee, Z-Wave, Bluetooth, BLE, satellite and Sigfox. The networks to be considered in the Life Cycle cost comparison are WiFi, cellular and LPWAN-private. Furthermore, the preferred network, from the tree is LPWAN-private, which indicates that the smallest costs are expected for the

LPWAN-private approach. Sigfox will be included in the financial analysis, on the condition that it is deployed and that the amount of required messages per day does not conflict with the available 140.

6.1.3 Life Cycle Cost Comparison

Some of the most important output parameters are shown in table 6.1. They give the reader some more understanding about the cost build up. The values before a "/" are only for the first approach, the values behind it for the second approach. All other values are for both approaches the same.

Table 6.1: Practical output use case 1, all approaches

<table>
<tr><td colspan="4" rowspan="2">Most important cost categories</td><td colspan="5">Network</td></tr>
<tr><td>Sigfox</td><td>LoRa-private</td><td>2G</td><td>4G</td><td>WiFi</td></tr>
<tr><td rowspan="2">CAPEX</td><td rowspan="2">Network installation</td><td>Number of base stations</td><td>[-]</td><td>0</td><td>4</td><td>0</td><td>0</td><td>3716</td></tr>
<tr><td>Travelling technical personnel</td><td>[hours]</td><td>0</td><td>1,75</td><td>0</td><td>0</td><td>10,8</td></tr>
<tr><td rowspan="4">OPEX</td><td rowspan="3">Battery replacements</td><td>Number of replacements</td><td>[-]</td><td>0/7</td><td>0/7</td><td>1/57</td><td>1/57</td><td>0/19</td></tr>
<tr><td>Cost buying batteries</td><td>[€]</td><td colspan="5">238230</td></tr>
<tr><td>Cost technical personnel hours</td><td>[€]</td><td colspan="5">161254</td></tr>
<tr><td>Subscription fee</td><td>Cost per end node/year</td><td>[€]</td><td>2</td><td>0</td><td>3,84</td><td>3,84</td><td>11 (per 4 routers)</td></tr>
</table>

6.1.3.1 Approach 1: 3 messages per day, compression factor 1

The telemetric case is adressed first. The amount of messages per day is 3. This comes down to 3 alarms per container per day, which seems rather high, but seen there are 8 parameters measured, still plausbile. Because of the low amount of messages, the ratio of battery lifetimes of LPWAN over cellular is 5, see table 5.12.

In table 6.2 all information is summarized of the different networks. The values are in millions of euros. It is clear that LoRa-private is the most cost efficient solution. 3G is not included but could be. However, due to lack of differing data, its cost course is the same as 4G and therefore excluded.

Table 6.2: Summary of costs for networks possible in use case 1

Summary [M €]								
Non - Discounted Network		Total	CAPEX	OPEX	Biggest contributor		Contribution	
					CAPEX	OPEX	CAPEX	OPEX
LPWAN	Sigfox	9,75	5,75	4,00	Communication chip	Subscription fee	5,35	4,00
	LoRa - Private	6,35	6,34	0,01	Communication chip	Own location	5,87	0,01
Cellular	2G	14,61	6,53	8,08	Communication chip	Subscription fee	6,13	7,68
	4G	15,42	7,34	8,08	Communication chip	Subscription fee	6,94	7,68
WiFi	WiFi	15,36	9,23	6,13	Communication chip	Subscription fee	6,13	6,13

The course of the costs over the lifetime is summarized in table 6.3. A visual interpretation is given in figure 6.2.

Table 6.3: Costs over lifetime for use case 1

Costs [M €]												
Non - Discounted		CAPEX	OPEX									Total
Network	Year	0	1	2	3	4	5	6	7	8	9	10	
LPWAN	Sigfox	5,75	0,40	0,40	0,40	0,40	0,40	0,40	0,40	0,40	0,40	0,40	9,75
	LoRa - Private	6,34	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	6,35
Cellular	2G	6,53	0,77	0,77	0,77	0,77	0,77	0,77	0,77	0,77	1,17	0,77	14,61
	4G	7,34	0,77	0,77	0,77	0,77	0,77	0,77	0,77	0,77	1,17	0,77	15,42
WiFi	WiFi	9,23	0,61	0,61	0,61	0,61	0,61	0,61	0,61	0,61	0,61	0,61	15,36

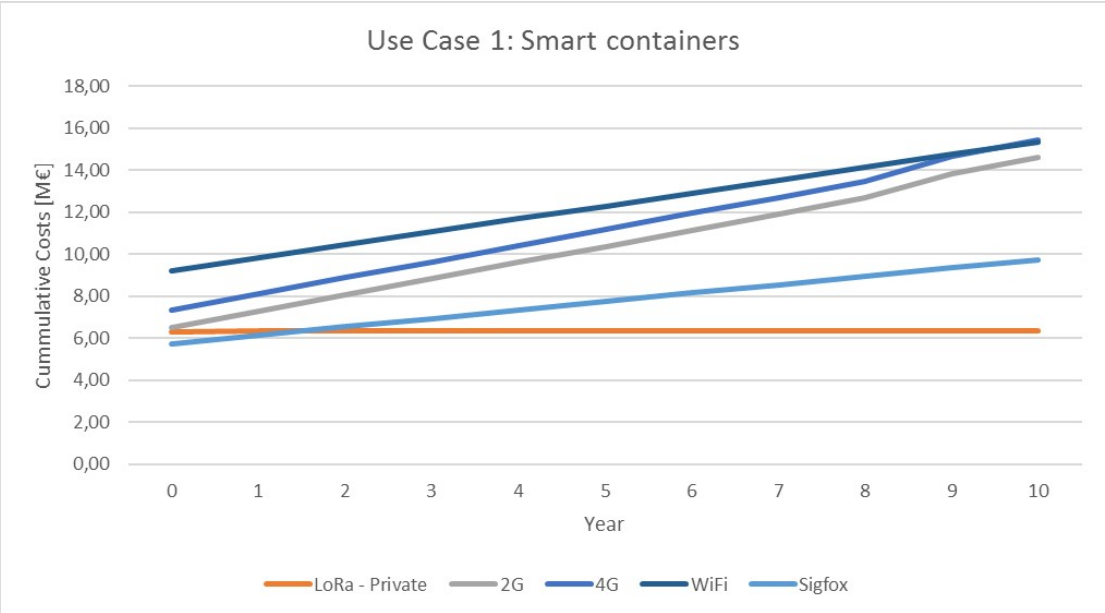

Figure 6.2: Smart Containers Port of Antwerp - Costs over lifetime

The major capital expenses in all networks are the the upfront buying of batteries (equal for all) and the communication chips. The communication chips for cellular, satellite and WiFi are slightly more expensive than those for LPWAN alternatives. Furthermore, chips at LoRa are slightly more expensive than their Sigfox alternative, which explains the initial cost difference between them. Cellular chips are still somewhat more expensive. In addition, for WiFi and LoRa-private, network have to be built. For WiFi this is a very high cost, for LoRa however it is limited seen that the area can be covered with only 3 base stations and each base station has a cost of only €4000, which is not much considering the total costs are around millions.

Regarding the OPEX, the steady increase with cellular options is due to the subscription fee and in year 9, their batteries have to be replaced. With WiFi, the same reasoning goes. Although here, the user has to pay a subscription fee based on the number of routers, rather than the amount of end nodes. The WiFi lifetime is somewhat higher than cellular, thus eliminating replacement costs.

The OPEX for Sigfox are driven by its subscription fee, which amounts €2 per end node per year. For LoRa-private, there is no subspriction fee, although there is a recurring cost of €25 per month per base station.

6.1.3.2 Approach 2: 100 messages per day, compression factor 5

Using 100 messages per end node per day, the purpose is no longer to alarm personnel but rather to accumulate data for further processing or other purposes. In this case, the exact amount of messages is not primordial, thus lets assume 100 messages per day. Of course, as the point here no longer is to alarm, but rather to accumulate data, the compression factor is enabled here and assumed 40, corresponding to data in table 5.12. Messages are compressed by factor 5 however, creating an effective ratio of 8. Table 6.4 summarizes the results over the lifetime.

TABLE 6.4: Costs over lifetime for use case 1 with 100 messages

Costs [M €]													
Non - Discounted		CAPEX	OPEX										Total
Network	Year	0	1	2	3	4	5	6	7	8	9	10	
LPWAN	Sigfox	5,75	0,60	1,00	1,00	0,60	1,00	1,00	1,00	0,60	1,00	1,00	14,54
	LoRa - Private	6,34	0,001	0,401	0,401	0,001	0,401	0,401	0,401	0,001	0,401	0,401	9,15
Cellular	2G	6,53	2,77	3,16	3,16	3,16	2,77	3,16	3,16	3,16	2,77	3,16	36,98
	4G	7,34	2,77	3,16	3,16	3,16	2,77	3,16	3,16	3,16	2,77	3,16	37,79
WiFi	WiFi	9,23	1,01	1,41	1,41	1,41	1,41	1,41	1,41	1,41	1,41	1,41	22,95

Cellular options clearly increase the most relative to their previous results, making them less attractive. WiFi does not increase by the same percentage as cellular does, but also increases more than LPWAN options. The reason that their costs increase is because the costs for battery replacements are far more frequent than for LPWAN network options. Cellular batteries are replaced 57 times over the lifetime, WiFi 19 times and LPWAN only 7 times. As a result, LPWAN options are by far the most price competitive options now. The total cost of a replacement is €400 thousand, this involves the actions of buying batteries and the hours technical personnel in replacing them.

6.1.4 Networks, their costs and trade-offs

Approach 1 and 2 are discussed simultaneously, since the same conclusions go for both.

LoRa-private is the most cost efficient solution in this case. This is logical since you want to connect a large amount of end nodes over a rather small area (on a global scale). There are however some trade-offs. When choosing LoRa-private, it is only possible to track and manage your smart containers in the port area. The added value is thus mainly for the port of Antwerp, which can more easily track containers. The added value for the client, and owner of the container however, is probably in the possibility to track his container wherever he goes over the globe.

A note on the previous paragraph. It is the port of Antwerp that wants to track these devices, not the visiting clients. If the clients want to benefit from the added value of connection outside of the port as well, and thus choose another network, the previous results are no longer correct. Roaming should be incorporated in cellular costs. Furthermore in the results here, the replacements of the battery only encompass the handling of the battery. Not the travelling to the end nodes in the field. It is however not possible to generate these costs. The devices run dry on battery when they are with the client, which can be anywhere around the world, and are thus nearly impossible to estimate. Furthermore and replacing them is no longer the responsibility of the port, this scenario is another use case, since this is observed from a visitor of the port his view, not from that of the port itself.

For global connection, clients would require a satellite solution, which is a factor 8.6 more expensive than the cellular option. This is also the reason that it is not included in the cost figures here, however it is possible. If however, the client would like to be connected on most parts of the world, a cellular option would be best, or less costly, Sigfox. Of course, this is on the condition that the Sigfox network is deployed there, which is not yet so at present. As already said, the costs for that scenario are not calculated here.

WiFi, although the high upfront costs also seems possible. The downside however is that the routers have to be placed on antennas, thus maintenance can be cumbersome (and this also explains the high CAPEX). Furthermore the antennas are closely spaced (200m), which may slightly hinder operations of the port. Finally, the same downside as for LoRa goes: the connection is limited to the port area. Furthermore, WiFi is inferfior to LoRa, since it offers no added technical value but is more expensive.

When deciding between Sigfox and cellular, it is important to recall that Sigfox can not locate the containers as accurately as Cellular options. However, Sigfox does offer an online platform where data can easily be accessed, this would have to be programmed with cellular options.

The conclusion is thus to use cellular (since Sigfox is not yet deployed) when the user wants to benefit from connection outside of the port as well. Otherwise, LoRa-private is the network to be selected. If Sigfox were deployed, the port would have to consider the restriction of 140 messages per day in case of approach 2. Furthermore, take into account the previous paragraph.

6.2 Use case 2: Medication transport

The functioning of certain medication strongly depends on the temperature they reside in and the exposure to light. Transport of this medication therefore has to submit to Good Medical Practices (GMP), such that is happens under the correct conditions and regulations. An international, established big pharmaceutical company wants to tracks the transport of their vaccinations up to the pharmacy. They want to track 2000 boxes over 4 countries. Upon arrival at the pharmacy, sensors are recovered from the box and utilised for the next transport.

Figure 6.3: Medication Transport

As it is not given in the context of the use case description, lets assume the distribution is happening over developed countries like France, Germany, Belgium and the Netherlands for example. A collection of Southern-EU countries or other locations in the world would satisfy this condition as well, but lets assume the pharmaceutical company distributes their products over the 4 countries stated here. These countries have a total area of 1073040 km. In all these countries, public cellular networks, as well as the Sigfox networks are present. However, with exception of some local spots, WiFi networks are not deployed nationally, nor freely accessible on that same scale.

6.2.1 Requirements

From the use case description, following listing of requirements can be derived:

- They want connection over a large area, encompassing 4 countries.
- Real time transmission is not a requirement. Frequent updates are sufficient, for example, once every 15 to 30 minutes for the case of data accumulation. Which

translates into a maximum of 96 messages per day. Sigfox, having messaging restrictions is capable up to 140 messages.

- The telemetric approach (only transmitting alarming situations) is also possible here. Let's assume the pharmaceutical company is only interested in these alarms, and thus not data collection in a first approach. In contrast to the previous use case, there is only single message required to transmit all information, because the limited amount of parameters (lightning, temperature).

- In a second approach, the amount of messages per day will again be 100. At this level, it is the magnitude which is important, not the exact amount. With these 100 messages, the purpose is to accumulate data.

- The lifetime of the application is in the order of days. Since upon delivery of the boxes, the sensors can be recovered and reused for the next transport. This eliminates the need to travel in order to replace batteries, as in use case 1. Of course, a longer battery life still offers a bonus since the replacement of the batteries still requires around 30 seconds (978.5 TMU at 60 Bdaux) of operation for a single device. Considering 2000 boxes, this can result in additional costs for shorter lifetimes.

- The transmitted data consists of temperature and light intensity values. These digits can be formatted such that they fit in a 12 byte framework, 12 bytes being the most restrictive possibility in this context. The data format is similar to the previous use case, the first digit indicating which parameter is measured, and the second indicating the level.

- The application is moving, possibly at considerable speeds like 120 kilometres an hour on European highways.

- Data encryption is a useful asset but is not an absolute necessity.

- The importance of certainty on the arrival of messages depends on the approach. In approach 1, the telemetric one, this is necessary in the opinion of the author. If the medication is exposed to a harsh environment, it can lose its functionality. If that message fails to arrive at the network, this will not be alarmed and the medication will just be sold, which completely undermines the purpose of this connection.

- Certainty of message arrival in approach 2, using 100 messages per day, is less strict. Messages arrive at a frequency of 15 minutes or higher. Therefore if 1 message fails to arrive, it is safe to assume that the harsh conditions will still apply 15 minutes later. The indication will thus be sent 15 minutes later, which should not pose a problem. The exact service level of Sigfox (the only one with uncertainy of arrival), will be detailed afterwards.
- Updates over the air or not relevant since the devices can be recovered after a short time in the field and updates can thus be applied to the device when they are recovered.

6.2.2 Decision Tree

Here again, the goal is to make an excluded, possible and preferred list of networks for this application. The possible list will again be evaluated in the Life Cycle Cost Comparison, where it is expected that the networks in the preferred list will give the optimal costs.

- In question 1, again the goal is to accumulate data. A proximity approach is not feasible since deploying a BLE network over a scale of 4 countries (with full coverage!) will be cumbersome and costly. This leads to question 2a, where again the conclusion is that a private protocol can be considered, resulting in question 3a.
- The location can be considered a land area, non remote. In question 3b, the answer is yes. The Sigfox network is deployed over the region as well as all cellular options (2G, 3G and 4G). The public WiFi option however is to be excluded since it is not deployed. In question 4 a, the amount of devices is 2000, which excludes Zigbee, Z-Wave and Bluetooth. From the question, also satellite does not seem the appropriate approach. It is indicated not to use satellite for more than 5000 devices, but of course these values are more or less arbitrary and their order of magnitude is far more important than the exact values. Of course it is still possible to use satellite, it is just not on the preferred list.
- Arriving at question 5a, again a definitive answer cannot be given, since the application lifetime is unknown. Of course, longer lifetimes are better since it requires

less frequent battery replacements. Although the transport cost in the replacement is eliminated, the physical action of replacement still accounts for a reasonable cost. For this reason LPWAN is preferred over other possible options.

- In question 3c, the coverage is nations, thus again recommending LPWAN. Cellular solutions are also advised but it should be noted that this is the second time that LPWAN is on the preferred list, compared to a single time for cellular.

- In the collection of technical questions, moreover questions 6a to 6f, none can be applied to this use case (distinction on amount of messages is already made), thus leading to question 7a without further restrictions.

- The application is moving, from time to time out of the range of an original base station, but always at maximum 120 kilometres an hour (European highway speed limits). WiFi can now also be added to the excluded list as a result of the travel speed. LPWAN and cellular networks also suffer from travel speeds, but are still applicable at the speeds required here.

- In question 8a, updates are not required.

The foregoing can be summarized by means of the lists. The excluded networks are Bluetooth, BLE, Zigbee, Z-Wave and WiFi. The network to be considered are Satellite, all cellular options and LPWAN. The preferred options still available is LPWAN (cellular not since it was marked as preferred only a single time).

6.2.3 Life Cycle Cost Comparison

Some of the most important output parameters are shown in table 6.5. They give the reader some more understanding about the cost build up. The values before a "/" are only for the first approach, the values behind it for the second approach (compression factor 5), and the third values are for the second approach (compression factor 20). All other values are for both approaches the same. The €0.48 for cellular is for roaming, the other one is regular.

TABLE 6.5: Practical output use case 2, all approaches

Most important cost categories				Network				
				Sigfox	LoRa-private	2G	4G	Irridium
CAPEX	Network installation	Number of base stations	[-]	0	12391	0	0	0
		Travelling technical personnel	[hours]	0	1283	0	0	0
OPEX	Battery replacements	Number of replacements	[-]	0/7/7	0/7/7	0/57/19	0/57/19	0/57/19
		Cost buying batteries	[€]	2532				
		Cost technical personnel hours	[€]	2609				
	Subscription fee	Cost per end node/year	[€]	6	0	3,84/5,76	3,84/5,76	467,4

6.2.3.1 Approach 1: 1 message/day, compression factor 1

Because the low amount of messages, battery power can be controlled efficiently for cellular technologies and the ratio of lifetime for LPWAN over cellular is 5, as also in table 5.12.

In table 6.6 all information is summarized for the different networks. All information is presented in thousands of Euros. 2G will in this case be the most cost-efficient approach to tackle the situation.

TABLE 6.6: Summary of costs for networks possible in use case 2

Summary [k €]								
Non - Discounted		Total	CAPEX	OPEX	Biggest contributor		Contribution	
Network					CAPEX	OPEX	CAPEX	OPEX
LPWAN	Sigfox	179,01	59,01	120,00	Communication chip	Subscription fee	53,87	120,00
	LoRa - Private	125642,77	14123,77	111519,00	network installation	Rented location	14058,91	111519,00
Cellular	2G	144,54	67,74	76,80	Communication chip	Subscription fee	62,60	76,80
	4G	153,49	76,69	76,80	Communication chip	Subscription fee	71,55	76,80
Satellite	Irridium	9763,40	415,14	9348,26	Communication chip	Subscription fee	410,00	9348,26

The course of the costs over the lifetime is summarized in table 6.7. A visual interpretation of the 3 most cost effective protocols (2G, 3G/4G, Sigfox) is given in figure 6.4.

TABLE 6.7: Costs over lifetime for use case 2

Costs [k €]												
Non - Discounted		CAPEX	OPEX									Total
Network	Year	0	1	2	3	4	5	6	7	8	9	10	
LPWAN	Sigfox	59,01	12,00	12,00	12,00	12,00	12,00	12,00	12,00	12,00	12,00	12,00	179,01
	LoRa - Private	1,4E+04	1,1E+04	1,1E+04	1,1E+04	1,1E+04	1,1E+04	1,1E+04	1,1E+04	1,1E+04	1,1E+04	1,1E+04	1,3E+05
Cellular	2G	67,74	7,68	7,68	7,68	7,68	7,68	7,68	7,68	7,68	7,68	7,68	144,54
	4G	76,69	7,68	7,68	7,68	7,68	7,68	7,68	7,68	7,68	7,68	7,68	153,49
Satellite	Irridium	4,2E+02	9,3E+02	9,3E+02	9,3E+02	9,3E+02	9,3E+02	9,3E+02	9,3E+02	9,3E+02	9,3E+02	9,3E+02	9,8E+03

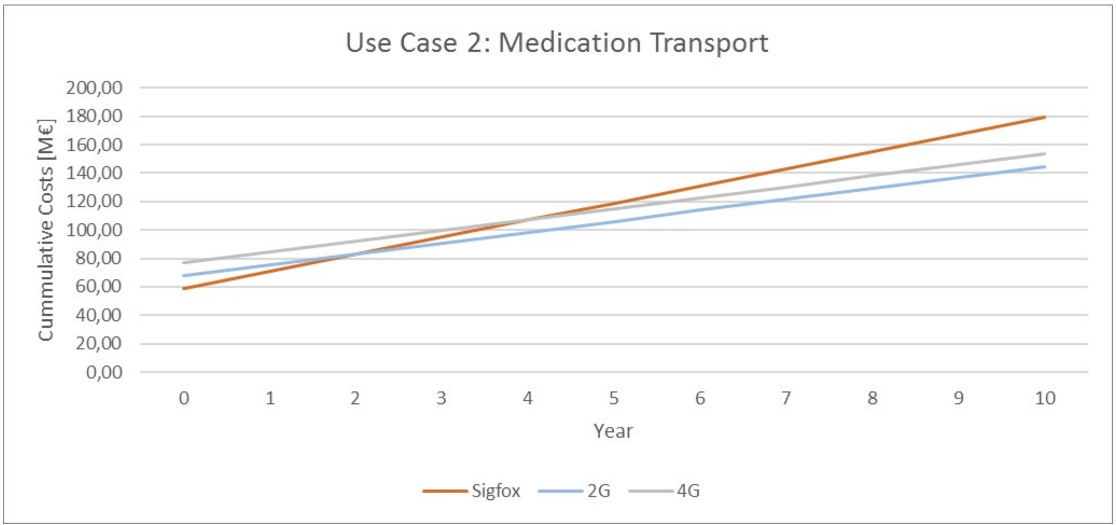

Figure 6.4: Medication Transport - Costs over lifetime

LoRa private, however the less costly approach in use case 1, does not offer a good approach here. The CAPEX are high because the amount of base stations to be installed. The OPEX are high, because of the maintenance (€25/month) and rental (€50/month) cost for each base station.

A satellite approach is very costly, which is simply because it is the more expensive variant of cellular options. Their chips are more expensive, and their subscription fee as well.

The major capital expenses in all networks (except for LoRa-private) are, again, the upfront buying of the communication chips and sensors with their batteries. Again, cellular is slightly more expensive than Sigfox in the buying.

The reason that Sigfox steadily increases by a higher value than cellular over the lifetime can be explained by the fact that the subscription fee for "Sigfox is less expensive for high amounts of end nodes". It is true that batteries have to be replaced more often for cellular technologies, but because the very low amount of messages, the batteries do not have to be replaced at all, for any technology.

6.2.3.2 Approach 2: 100 messages, 2 different compression factors

Here as well, what happens when there are 100 messages per day? In the data accumulation use case, and look at the impact on the results. The results are generated for both compression factors 5 and 20. Results are shown in tables 6.8 and 6.9. It should be remarked that in this case, the ratio of lifetimes LPWAN over cellular is 40, because the battery usage can not be controlled as efficiently as in approach 1, see also table 5.12.

TABLE 6.8: Costs use case 2: 100 messages per day and compression factor 5

Costs [k €]													
Non - Discounted		CAPEX	OPEX										Total
Network	Year	0	1	2	3	4	5	6	7	8	9	10	
LPWAN	Sigfox	59,01	18,00	23,14	23,14	18,00	23,14	23,14	23,14	18,00	23,14	23,14	274,99
	LoRa - Private	1,4E+04	1,1E+04	1,1E+04	1,1E+04	1,1E+04	1,1E+04	1,1E+04	1,1E+04	1,1E+04	1,1E+04	1,1E+04	1,3E+05
Cellular	2G	67,74	33,38	38,52	38,52	38,52	33,38	38,52	38,52	38,52	33,38	38,52	437,55
	4G	76,69	33,38	38,52	38,52	38,52	33,38	38,52	38,52	38,52	33,38	38,52	446,49
Satellite	Irridium	4,2E+02	9,6E+02	9,7E+02	9,7E+02	9,7E+02	9,6E+02	9,7E+02	9,7E+02	9,7E+02	9,6E+02	9,7E+02	1,0E+04

TABLE 6.9: Costs use case 2: 100 messages per day and compression factor 20

Costs [k €]													
Non - Discounted		CAPEX	OPEX										Total
Network	Year	0	1	2	3	4	5	6	7	8	9	10	
LPWAN	Sigfox	59,01	18,00	23,14	23,14	18,00	23,14	23,14	23,14	18,00	23,14	23,14	274,99
	LoRa - Private	1,4E+04	1,1E+04	1,1E+04	1,1E+04	1,1E+04	1,1E+04	1,1E+04	1,1E+04	1,1E+04	1,1E+04	1,1E+04	1,3E+05
Cellular	2G	67,74	12,82	12,82	17,96	12,82	17,96	12,82	17,96	12,82	12,82	17,96	216,51
	4G	76,69	12,82	12,82	17,96	12,82	17,96	12,82	17,96	12,82	12,82	17,96	225,45
Satellite	Irridium	4,2E+02	9,4E+02	9,4E+02	9,5E+02	9,4E+02	9,5E+02	9,4E+02	9,5E+02	9,4E+02	9,4E+02	9,5E+02	9,8E+03

For compression factor 5, the amount of battery replacements is 7 (LPWAN), 57 (Cellular, satellite) and 19 (WiFi). In the case of compression factor 20, the amount of replacements is 7 (LPWAN), 14 (Cellular, satellite) and 7 (WiFi).

Again LPWAN is the most attractive solution, because of less frequent battery replacements in comparison with other technologies. An additional result is that increasing the compression factor clearly has a big impact, when comparing tables 6.8 and 6.9.

Recall the discussion on the topic of certainy of message arrival. Sigfox is the only one with uncertainty upon arrival. Estimated, their SLA for a single message is around 97%. Of course, since they send each message in threefold, their effective SLA is 99.9973%. Since messages are sent within a 15 minutes interval, there would be 2 data points instead of 3 in a 30 minute duration. Since an exposure of maximum 29 minutes (the duration where you lack data) to an elevated temperature or illumination level is not harmful to most medication, this service level does not pose a tread in practice. Their SLA can, if necessary, be further increased by sending each message more than 3 times.

6.2.3.3 Notion: roaming

The application is located over 4 different countries. In all previous calculations, there is no additional roaming cost. In other words, it is assumed that products manufactured/picked up in a certain country are also delivered in that same country. Otherwise, there is a roaming cost addition required.

From all technologies included here, cellular is the only one requiring a roaming cost add-on. The author does not have specific information on the roaming costs because the subscription fee pricing in this paper is based on a private tender and that information is not publicly available. Therefore, the roaming costs are not standard set and can not be found. They are assumed to increase the original subscription fee by 50%. Of course, they are the ideal input for the sensitivity analysis afterwards.

The results for cellular, for both approaches, are presented in table 6.10, 6.11 and 6.12. The cellular options now become slightly more expensive than the Sigfox one for 1 message. For 100 messages with factor 5, they are much more expensive and in the case of compression factor 20, they are less expensive. Compared to other options than Sigfox, they still perform better with regard to costs.

TABLE 6.10: Roaming enabled, 1 message per day

Costs [k €]												
Non - Discounted		CAPEX	OPEX									Total
Network	Year	0	1	2	3	4	5	6	7	8	9	10	
Cellular	2G	67,74	11,52	11,52	11,52	11,52	11,52	11,52	11,52	11,52	11,52	11,52	182,94
	4G	76,69	11,52	11,52	11,52	11,52	11,52	11,52	11,52	11,52	11,52	11,52	191,89

TABLE 6.11: Roaming enabled, 100 messages per day, compression factor 5

Costs [k €]												
Non - Discounted		CAPEX	OPEX									Total
Network	Year	0	1	2	3	4	5	6	7	8	9	10	
Cellular	2G	67,74	37,22	42,36	42,36	42,36	37,22	42,36	42,36	42,36	37,22	42,36	475,95
	4G	76,69	37,22	42,36	42,36	42,36	37,22	42,36	42,36	42,36	37,22	42,36	484,89

Table 6.12: Roaming enabled, 100 messages per day, compression factor 20

Costs [k €]													
Non - Discounted		CAPEX	OPEX										Total
Network	Year	0	1	2	3	4	5	6	7	8	9	10	
Cellular	2G	67,74	16,66	16,66	21,80	16,66	21,80	16,66	21,80	16,66	16,66	21,80	254,91
	4G	76,69	16,66	16,66	21,80	16,66	21,80	16,66	21,80	16,66	16,66	21,80	263,85

6.2.4 Networks, their costs and trade offs

The competition is between cellular and Sigfox. In all above tables, these 2 are always much more competitive than the others, thus one of these should be selected.

The downside of using Sigfox is the amount of messages per day. If the client wishes to sent more than 140 messages per day, there is no choice but cellular left. In a telemetric approach however, 140 messages per day will never be reached and thus Sigfox is a safe choice. However, it should be considered that messages can be lost with Sigfox. One reason of not receiving messages is their SLA, the other being that transport on highways can hinder their communication. It is not clear at what exact speeds Sigfox stops working or how travel speed relates to their SLA. But it is sure that they will suffer from some drop in their SLA at high speeds.

In approach 2, with 100 messages per day and compression factor 5, Sigfox is significantly cheaper than cellular, roaming included or not. Technically however, the user is limited to 140 messages per day using Sigfox. This should be considered in the selection process. Furthermore, the items mentioned in the previous paragraph should be considered.

When the compression factor 20 is applied to the cellular messages, still in approach 2, the cost of cellular becomes cheaper again, even when including roaming. Therefore, cellular should be selected.

6.3 Use case 3: Arrival times at De Lijn public transport

De Lijn is a Belgian public company who offers transport by bus over the major parts of the country. Different buses cover different routes. Each route is characterized by bus stops, where the bus picks up and drops of customers of their service. The buses drive at fixed hours, such that clients can plan when they want to take the bus. Due to traffic congestion, mostly in urban environments, they suffer from drops in their service level, more specifically the buses do not arrive in time at their stops. They want to reschedule their arrival timetables, using real time information on the buses locations. The effective arrival times can then be used to inform their customers and consequently increase their service level and customer satisfaction.

FIGURE 6.5: Bus stop De Lijn

There is a big difference in comparison with other use cases here. It is possible for a small installation cost add-on to wire the end nodes to the battery of the bus. The end nodes would still have batteries, such that they can remain active whilst the engine of the bus is not running. However, when the engine of the bus is running, the batteries are recharged and there is no need for replacement. The cost for wiring the end node would be smaller compared to the other use cases simply because the power source (the bus) is nearby and would outweigh the operational expenses in the long term. This is logical because the amount of messages per day is rather high (explained later) and thus for each technology the batteries would have to be changed at least several times.

The network of De Lijn covers almost the whole of Belgium, with some exceptions of remote and less inhabited areas. Some parts of Belgium are urban and congested, this is where they experience major quality issues, other parts are rural, but they want to include these parts of their networks also in the analysis. The total area of Belgium amounts to 30 528 km. To have an impression of the magnitude of the amount of bus stop in one day it is useful to look at for example the route Sint-Niklaas to Dendermonde. This route takes the bus 59 minutes, thus approximately 1 hour and requires 32 bus stops. An average bus thus stops around 30 times an hour. Furthermore the buses drive form 06:00 in the morning till 00:00 at night. Of course not all buses are driving those 16 hours, but more in the range of 14 hours. Therefore, an average bus makes an estimated 420 stops per day.

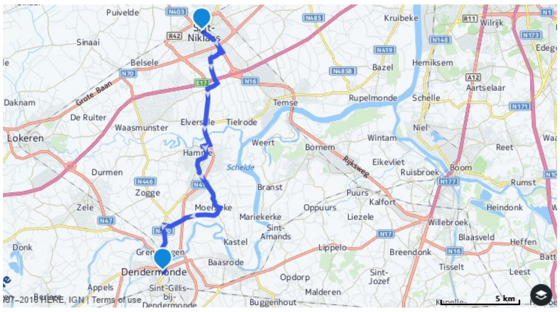

FIGURE 6.6: De Lijn route of Sint-Nikaas to Dendermonde

Furthermore, on the topic of which networks are available in Belgium, there are several network providers of cellular networks and the Sigfox network is also deployed, even on a very dense scale. A nationwide WiFi network is not present, although there is a minor coverage in some major cities, but that will not prove sufficient. As LPWAN, LoRa public is also increasingly present, but there is no pricing available. This will be covered in more detail in chapter 7.

Finally, there are two approaches in which this problem can be tackled, the implementations involving differences in what the structure looks like. In a first method, a transceiver would be placed in each bus. These transceivers send intermittent messages to a network, that is deployed over the whole country, remark that this will typically be WAN options. The data they sent are the coordinates of the bus at that time, which requires GPS positioning. In a second approach, transceivers are also deployed inside the buses, but in addition a beacon is placed at every bus stop, thus aiming at a BLE solution. In this case, the coordinates are fixed (being the location of the beacon) and thus can be stored in the beacon. When a BLE transceiver (inside the bus) passes by the beacon, it will send its serial number (thus identifying the bus) and the beacon can register the time that a certain bus passed that bus halt. The advantage of the latter case over the former is that messages are always sent at bus stops, thus the data acquiring is very consistent. This is in contrast to the non-beacon scenario, where messages would be sent at a specified instance rather than location, for example each 15 minutes.

6.3.1 Requirements

The following lists all the requirements that networks should offer:

- There are a large number of devices to be connected over the area of Belgium.
- The higher the frequency of the messages, the better. This is easiest explained by an example. Take Sigfox, for instance, that is capable of sending a maximum amount of 140 messages per day. Furthermore, let's assume that a bus drives/is operational 8 hours per day. This comes down to approximately 1 message every 3.5 minutes. The client that uses the services of De Lijn, will look on the messaging board with real time information. The fact that a message arrives each 3.5 minutes, means that there is an uncertainty of 3.5 minutes on the information on the board. A higher amount of messages, reduces this uncertainty. Therefore high messaging frequency is an advantage.
- The lifetime of the end node is not an important factor here, since they are wired.
- The data per message to be sent is small, thus 12 bytes is sufficient. High data rates are neither required.
- The transceivers should be able to send data while moving, at maximum speeds of 70 kilometres an hour.
- Encryption of data is not a necessity, since this information is worthless to third parties.
- Certainty of message arrival is neither a necessity since the lack of a few data points will not lower the service level, and if it does, the consequences will not be severe.
- Updates over the air can be an added value, but probably this will never be required.

6.3.2 Decision Tree

Here again, the principle of 3 lists is the same, and the walk through will be elaborated for both approaches. Both approaches will merge their solutions at the Life Cycle Cost Comparison.

6.3.2.1 Approach 1

In this first approach, a proximity solution is chosen. This immediately stops the walk through at question 1 and recommends a BLE network. In this network, beacons are deployed at each bus stop. The buses themselves will be equipped with wired BLE end nodes.

6.3.2.2 Approach 2

- In this second approach, the other data accumulation option is chosen, excluding BLE, Bluetooth, Zigbee and Z-Wave and leading to question 2a. Here again, it is possible to develop a proper protocol.
- In question 3a, one chooses the land area, non remote option, leading to question 3b. Here again, the network of Sigfox is present, as well all cellular option (2G to 4G). The public WiFi network however is not deployed on a national scale and is thus excluded. The amount of devices in question 4a is higher than 5000, thus removing satellite from the preferred list permanently (since it is an indicative question).
- The lifetime of the end nodes in question 5a, is not relevant.
- The scale of the network in question 3c can be considered as in between industry and nations (since Belgiums surface is rather small), but the options are the same. Cellular, along with LPWAN is added to the preferred list.
- In the series of technical question, the only restrictive one might be the amount of messages per day, thus 6c. However, 140 messages per day can still be sufficient. Therefore, Sigfox is still possible but its applicability depends on whether or not De Lijn sets further specifications to this regard.
- The other questions do not impose further restrictions. Thus the summary for this approach gives an excluded list of Zigbee, Z-Wave, Bluetooth, BLE and WiFi. The possible list contains networks like satellite, cellular and LPWAN, while LPWAN and cellular are on the preferred list. Whether or not Sigfox should be included depends on further specifications of De Lijn with regard to the amount of messages per day.

6.3.3 Life Cycle Cost Comparison

Because it is a cost comparison, the wiring of the end nodes is not taken into account since it involves a one time action and furthermore it is the same for each network and will thus not influence the cost outcome.

Some of the most important output parameters are shown in table 6.13.

TABLE 6.13: Practical output use case 3

Most important cost categories				Network					
				Sigfox	LoRa-private	2G	4G	Irridium	BLE
CAPEX	Network installation	Number of base stations	[-]	0	973	0	0	0	332895
		Travelling technical personnel	[hours]	0	58,7	0	0	0	1100
OPEX	Battery replacements	Number of replacements	[-]	0	0	0	0	0	21
		Cost buying batteries	[€]	0					412425
		Cost technical personnel hours	[€]	0					82443
	Subscription fee	Cost per end node/year	[€]	12	0	3,84	3,84	467,4	0

The costs are summarized in table 6.14. All costs are in thousands of Euros.

TABLE 6.14: Summary of costs for networks possible in use case 3

Summary [k €]								
Non - Discounted Network		Total	CAPEX	OPEX	Biggest contributor		Contribution	
					CAPEX	OPEX	CAPEX	OPEX
LPWAN	Sigfox	386,80	73,60	313,20	Communication chip	Subscription fee	70,30	313,20
	LoRa - Private	4,1E+03	1,3E+03	2,8E+03	network installation	Own location	1,2E+03	2,8E+03
Cellular	2G	185,22	85,00	100,22	Communication chip	Subscription fee	81,69	100,22
	3G	196,90	96,67	100,22	Communication chip	Subscription fee	93,37	100,22
	4G	196,90	96,67	100,22	Communication chip	Subscription fee	93,37	100,22
Satellite	Iridium	2,1E+06	1,4E+05	2,0E+06	Network installation	Subscription fee	1,4E+05	2,0E+06
PAN	BLE	1,8E+04	7,9E+03	1,1E+04	Network installation	Battery purchase	7,8E+03	8,9E+03

It is clear that cellular offers the most cost efficient approach in this case, followed by Sigfox. Satellite is, as can be seen a much more expensive option, a fact that is not surprising since the subscription fee is €38.95 per month per device, compared to €0.32 in case of cellular connection. The same reasoning goes for Sigfox, the subscription fee simply is higher, being €9 per year per device. Again, recall the discussion in use case 1 on how the subscription fee for Sigfox is more expensive than cellular when the amount of end nodes is limited.

However that the concept of the Bluetooth Low Energy approach could work practically, its costs seem to be much higher than other options. The reason the CAPEX is so high, is simply because the network installation is so costly. Covering all bus stops in Belgium requires 332895 beacons (simply the estimated amount of bus stops). Considering there are only approximately 2610 buses, the ratio of beacons per bus are out of scale. The OPEX of this approach are also rather high, not originating from a subscription fee, but because the beacons are not battery powered and they have to be replaced every 1.4 years. Since the amount of beacons is high, this costs are also high. Now one could argue to install less beacons, for example only covering 20% of all bus stops. In this case, the service level would drop compared to the other approaches. Furthermore, even at 20% of its current cost, it would still not be a competitive option.

As for LoRa-private, the installation of base stations is the most important factor in the high CAPEX. Their OPEX are high as well because a fee of €75 per month has to be paid for renting the location where the base station is installed and maintaining it. It is clear that LoRa-private is not suited for large area deployments with a limited amount of end nodes.

The costs over the lifetime of the different options are summarized in table 6.15. Figure 6.7 gives a visual representation of the most cost effective solutions. Again there is no distinction between 3G and 4G.

TABLE 6.15: Costs over lifetime for use case 3

Costs [k €]													
Non - Discounted		CAPEX	OPEX										Total
Network	Year	0	1	2	3	4	5	6	7	8	9	10	
LPWAN	Sigfox	73,60	31,32	31,32	31,32	31,32	31,32	31,32	31,32	31,32	31,32	31,32	386,80
	LoRa - Private	1298,14	281,10	281,10	281,10	281,10	281,10	281,10	281,10	281,10	281,10	281,10	4109,14
Cellular	2G	85,00	10,02	10,02	10,02	10,02	10,02	10,02	10,02	10,02	10,02	10,02	185,22
	3G	96,67	10,02	10,02	10,02	10,02	10,02	10,02	10,02	10,02	10,02	10,02	196,90
	4G	96,67	10,02	10,02	10,02	10,02	10,02	10,02	10,02	10,02	10,02	10,02	196,90
Satellite	Iridium	136956,78	2,0E+05	2,0E+05	2,0E+05	2,0E+05	2,0E+05	2,0E+05	2,0E+05	2,0E+05	2,0E+05	2,0E+05	2,1E+06
PAN	BLE	7858,15	1,0E+03	1,0E+03	1,0E+03	1,0E+03	1,0E+03	1,0E+03	1,5E+03	1,0E+03	1,0E+03	1,0E+03	1,8E+04

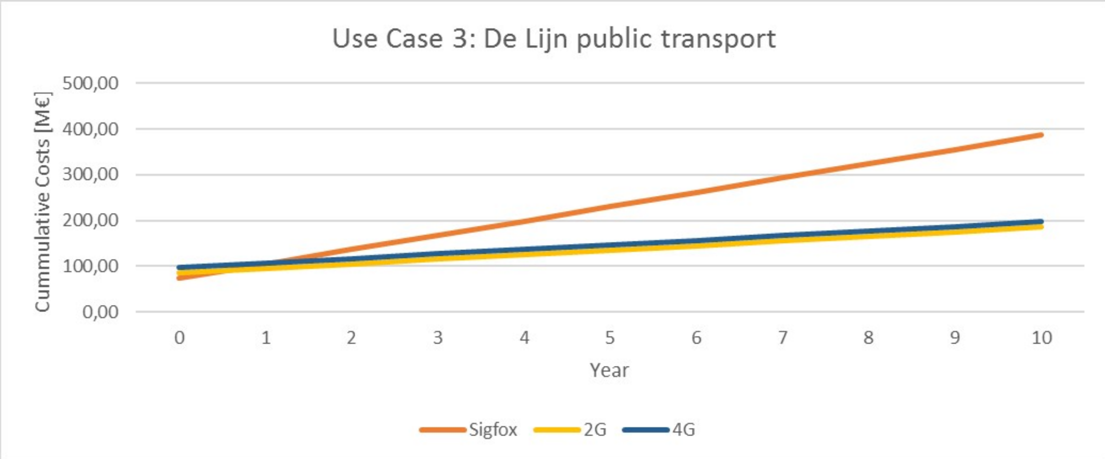

FIGURE 6.7: De Lijn Tracking - Costs over lifetime

6.3.4 Networks, their costs and trade offs

In this case, the cellular approach is the most cost efficient one and should be picked. There are not any technical downsides to it, since the messaging frequency can be as high as desired, which is not the case with Sigfox, thus enabling higher service levels. Furthermore, the battery constraint is no longer valid, since devices are wired.

6.4 Overall conclusion

6.4.1 LPWAN and cellular

The use cases presented here were very different. What is apparent from use case 3 in particular, is that from a cost point of view, LPWAN are only a good option when the battery power is an important factor. In use case 3, it could also have been predicted that cellular would have been less costly, this is a direct consequence from table B.5 in Appendix B.

Noting the first paragraph, even more is to be said after including use cases 1 and 2. Overall, in both cases LPWAN and cellular were competitive to some extent. This follows from the setup of those cases. In both cases, end nodes are collected automatically after a certain period. If however the end nodes remain in the field, and are only retrieved when their batteries have to be replenished, these travel costs would be included as well. These are significant for larger areas, and LPWAN networks would be selected at that point.

On the topic of Sigfox it is important to realise that this network has the most technical restrictions. Location accuracy, messaging frequency, message size etc. should all be considered beofre selecting it. In contrast there is LoRa with less technological restrictions. Their private option only seems feasible where the ratio amount of nodes over surface to cover is high. Therefore it was a good option, from an economic point of view, in use case 1 but not in the others. The public LoRa therefore is very promising (since if suffers less from technological constraints), but all will depend on their subscription fee.

6.4.2 Satellite

Satellite pricings are always many factors higher than the cellular option for example. This is because of the subscription fee which is a factor 120 higher. As technically satellite does not offer any added-value over cellular, it should only be applied when cellular solutions are not applicable. This is only the case when the user requires worldwide coverage or when his application is located in remote areas, where there is no cellular network available.

6.4.3 WiFi and other LANs

WiFi was not a good approach in any of the use cases here. This was to be expected because of the magnitude of the areas compared to the range of a router. LoRa-private will always be a better option than WiFi, with the exception of small scale deployments. A guideline would be for example, when the amount of end nodes is small (¡500 f.e.) and the area to cover as well (¡ 1 km^2 f.e.) then the upfront cost of the LoRa base station can not be justified and WiFi will be cheaper.

The same goes for Zigbee and Z-Wave, they are only competitive for small scale deployments. Furthermore, they should only be used when they offer added value over WiFi. Their added value is in the fact that the automation in the end nodes is already programmed, which is not the case with WiFi.

6.4.4 PANs

Bluetooth was never considered in the use cases, it should only be used when the sole purpose is to eliminate wiring on short distance, with acquiring access to any outside network.

Bluetooth Low Energy seemed a good approach in case 3, but the upfront costs were simply too high. This confirms that the (probably best) market scenario/implementation for this technology is what they propose themselves. In shops to aid customers or the enhance advertising possibilities and other proximity services.

Large scale deployments are also possible (and will apparently be expensive) and therefore they should be used when the purpose of the use case is as described above. Other battery saving technologies are not built for proximity services (Base stations too expensive for LoRa and Sigfox message limitation) and cellular or other options would be too battery consuming. WiFi would not be applicable neither since they require identification to the network. Zigbee and Z-Wave do not support these use cases since they have to identify nodes to the network. Furthermore, the beacon approach is very unique in a sense that only coverage is required over 5 metres around it. There are several such spots of interest, with beacons, but all areas around it don't require coverage.

Chapter 7

Sensitivity Analysis

Sensitivity analysis is the study of how the uncertainty in the output of a mathematical model or system (numerical or otherwise) can be apportioned to different sources of uncertainty in its inputs. [16]

Several input parameters can be varied by user input and some of these are rather uncertain. Other already fixed inputs, such as for example the time it takes to change a single battery, are estimations, and therefore could also deviate from its set value. With a sensitivity analysis, the outcome is determined, for all varying input. It is possible, taking into account these variations, that the most cost efficient network is not the most robust one to these deviations and therefore, another network might be a safer choice.

This sensitivity analysis is tackled case by case. For each use case, first all possible input parameters for the sensitivity analysis are listed. Then the results of this analysis are presented.

Some of the uncertain parameters are not related to any use case, but rather to the model. Therefore, these common parameters among the use cases are listed here. Then in the following sections, the case-related additional parameters will be discussed.

Finally, the simulation is performed in "Crystal Ball". The sensitivity analysis consists of a Monte Carlo simulation, where the amount of runs is user specified. Monte Carlo analysis allows inputs of different variables to follow a statistic distribution. After specifying the distribution, the program assigns random values to all parameters (here the common values discussed in the next section), taking into account their specified distribution. It then calculates the outcome parameters (here the total cost of each network) and maps it in charts. Monte Carlo simulations require at least 1000 runs, although the industry standard is 10000. The amount of runs here are 100000.

7.1 Common uncertain input parameters

In table 7.1 the parameters used in all use cases are presented with their assumed distributions and characteristics.

TABLE 7.1: Sensitivity analysis input parameters in each use case

General (all use cases)				Sensitivity Analysis Input				
Parameter	Unit	Comments	Original value	Min	Mean	Max	Additional parameter	Distribution
Technical Personnel	€/hour		75	55	75	80	/	Uniform
LoRa subscription fee	€/year		None	/	8	/	std: 0,5	Normal
Owned location	€/month		25	/	25	/	scale: 2,5	Minimum extreme distribution
Rented location	€/month		75	/	75	/	scale 5	Minimum extreme distribution
2G subscription fee	€/month		0,3	/	0,3	/	/	Custom
Economies of scale	%	From 100+ items	0,9	0,87	0,9	0,91	Alpha: 2, Beta: 3	Beta
Economies of scale	%	From 10000+ items	0,81	0,75	0,81	0,84	Alpha: 4, Beta: 3	Beta

Reasoning behind the different distributions:

- Technical personnel: uniformly distributed. €75 is rather a maximum hourly loan for technical personnel. The applications of the different use cases are focused in Belgium and its neighbouring countries, where these magnitudes are realistic. However, using public tenders, it is possible to obtain more competitive pricing. The distribution is uniform since there is no information on their relative frequencies.

- The LoRa public subscription fee will be around €8. Since its pricings are not yet public, a normal distribution is the safest assumption. Using a standard deviation of €0.5, around 95% of the values are between €7 and €9.

- The owned and rented location are estimated values. Recall that the composition of the "owned location" pricing consists of €15 for internet access and €10 for electricity and maintenance. These assumptions are rather high. Therefore a minimum extreme distribution is applied, which favors values lower than the mean. The same reasoning goes for "rented location", where a €50 additional fee is included for rental. Since these €50 are very high, the scale relative to the mean is higher here than in the former case.

- The cellular subscription fee used in the previous chapters is from real tenders of Belgian telecommunication providers. The exact values can differ a little from client to client since they are not public and pricing comparison is therefore hindered. The custom values range from €0.28 to €0.33 in a normal distributed fashion.
- The obtained discount upon buying large quantities of items is very sensitive to the amount bought and the nature of the items (Image 70 % discounts for fashionable clothing). The Beta distribution is a skewed Gaussian distribution. The first economies of scale is slightly scaled to the right, the second one slightly to the left.

7.2 Use case 1: : Smart containers at the port of Antwerp

7.2.1 Parameter set 1: 3 messages, compression factor 1

The additional parameters of interest are shown in table 7.2.

TABLE 7.2: Additional SA input parameters use case 1

Parameter	Unit	Original value	Min	Mean	Max	Additional parameters	Distribution
Battery exchange	TMU	978,5	/	978,5	/	300	Maximum extreme distribution
Cost per battery	€	1,43	1,3	1,43	2,5	Alpha: 2, Beta: 10	Beta
Amount of messages	Mes/day	3	/	3	/	Prob: 0,6 ; Trials : 3	Binomial
Lifetime ratio LPWAN/cellular	[-]	5	/	5	/	Scale: 0,5	Maximum extreme distribution

Reasoning behind the different distributions:

- The battery exchange time originates from a time studies. Since these time studies are generally very strict and particularly used in highly standardized environments, their results could not be all to suited for this applications. Furthermore, there is a lot more variety to account for than in standardized production. For this reason, the computed value (987.5 TMU, or around 30 seconds) is regarded as a minimum and the impact is higher values is checked upon here. The maximum extreme distribution allocates higher probabilities to lower values, but higher extremes are also possible. Using a scale of 300, values of twice the original amount are not unlikely.

- The cost price per battery here was obtained during online research. If one would search for it, you would remark these prices are very volatile. Furthermore, these prices can change from day to day. Of course, a user will always search for the cheapest available alternative, therefore the beta distribution still allocates the highest probabilities to prices close to the original.
- The amount of messages is user specified, and the values in the research here were assumptions. Empirical data can give good impression to this regard. Of course, considering lack of reliable data, this is an ideal input for the SA. The binomial distribution considers values from 0 to 3 messages per day, allocating the highest likelihood to 1 and 2 messages per day.
- The lifetime is very reliable on the actual usage. Its variation can have an impact, however in this first approach its impact is expected to be limited. The amount of messages is low, thus the replacements are low.

Satellite details are not included, because even if the SA varies it subscription fee, its costs will still be much higher than all others and other options are possible here.

7.2.2 Parameter set 2: 100 messages, compression factor 5

In section 7.2.1 the amount of messages was low. Here the amount of messages will be 100. Additionally, the LoRa subscription fee will be assigned a different value, this should give an impression of when it becomes competitive. Apart from the parameters set forth in table 7.3, the parameters remain the same.

TABLE 7.3: Use case 1, research 2: input parameters

Parameter	Unit	Original value	Min	Mean	Max	Additional parameters	Distribution
Battery exchange	TMU	978,5	/	978,5	/	300	Maximum extreme distribution
Cost per battery		1,43	1,3	1,43	2,5	Alpha: 2, Beta: 10	Beta
Amount of messages	Mes/day	100	/	100	/	Min: 30 ; Max: 130	Uniform
Lifetime ratio LPWAN/cellular	[-]	40	/	40	/	Scale:2	Min extreme

The input values are such that a wide range of scenarios can occur. This can indicate whether or not future research can be interesting. Since there is no exact information on the amount of messages, its distribution is assumed uniform.

The ratio of lifetimes is assumed on 40 here, corresponding table 5.12, since the amount of messages is high. Fluctuations are assumed to follow the max extreme distribution, allowing smaller values until 35.

7.2.3 Results

7.2.3.1 Parameter set 1: 3 messages per day, compression factor 1

Results are shown in table 7.4 in millions of euros. The minimum, mean, maximum and standard deviation are parameters that occurred during/originate from the Monte Carlo simulation. A distribution is fitted to the Monte Carlo output. Finally, the most sensitive parameters are available. These parameters are responsible for the indicated percentage in the variation of the total result.

Table 7.4: Output SA use case 1

Output chart						Most sensitive parameters	
Network	Minimum	Maximum	Mean	Std	Fitted distribution	Parameter	Percentage
Sigfox	8,64	10,01	8,96	0,41	Lognormal	Battery exchange	72,8
						Amount of messages	17
LoRa - Public	17,2	26,72	22,26	1,00	Lognormal	LoRa subscription fee	99,7
						Battery exchange	0,2
LoRa - Private	6,22	6,68	6,34	0,04	Lognormal	Battery exchange	80,2
						Economies of scale (2)	9,9
2G	13,11	15,31	14,04	0,42	Beta	Cellular subscription fee	91,5
						Amount of messages	4,3
4G	13,87	16,09	14,87	0,42	Beta	Cellular subscription fee	91,3
						Amount of messages	4,2
WiFi	14,88	15,75	15,22	0,14	Beta	Technical personnel	88
						Battery exchange	10

In general in a sensitivity analysis, the most important outputs are those with a lot of variation, which is indicated by a large standard deviation (in comparison with the mean) or also possible a large difference between the minimum and maximum. Other outputs/networks, more robust to variation, will influence the decision process less.

The minimum for cellular is still higher than the maximum for Sigfox. Since its variation is also limited, it will never achieve the same cost ranges. Furthermore, it should be noted that roaming has limited influence here, it only has indirect influence by the cellular subscription fee.

It is also clear that Sigfox can impossibly be competable with LoRa private. However recall that the added value of Sigfox (if deployed!) is that there is coverage in more places than solely the port of Antwerp.

LoRa public is a rather expensive solution, even compared to cellular options. The subscription fee is responsible for almost all variation. More concrete results are possible when more detailed subscription fee information is made public.

Future research is not really required here, as the results are fairly stable around their input values.

7.2.3.2 Parameter set 2: 100 messages per day, compression factor 5

Table 7.5 summarizes the results for the different options.

TABLE 7.5: Output SA use case 1, research 2

Output chart						Most sensitive parameters	
Network	Minimum	Maximum	Mean	Std	Fitted distribution	Parameter	Percentage
Sigfox	13	25,38	17,46	3,49	Pareto	Amount of messages	82,9
						Battery exchange	15,2
LoRa - Public	19,88	31,09	25,02	1,22	Lognormal	LoRa subscription fee	69,5
						Amount of messages	18,9
LoRa - Private	7,59	13,99	9,1	0,70	Beta	Amount of messages	65,4
						Battery exchange	30,8
2G	21,88	73,99	36,65	5,44	Gamma	Amount of messages	63,4
						Battery exchange	26,4
4G	22,68	74,81	37,41	5,44	Gamma	Amount of messages	63,4
						Battery exchange	26,4
WiFi	17,59	36,32	22,87	1,90	Gamma	Amount of messages	61,2
						Battery exchange	26,4

LoRa public now becomes a viable option for values near its minimum. Those values are characterised by subscription fees around €4.5, thus if the public LoRa is available for such costs, it is a decent option.

Furthermore the amount of messages seems to have an impact on the costs for LPWAN networks. The variation of Sigfox as well as LoRa private is mainly due to the amount of messages. Increasing the amount of messages, increases the frequency of battery replacements.

The variation of the cellular options is much higher than for all other options. The amount of messages has a great impact, which results from a differing amount of battery replacements. This indicates that future research requires more input on the exact amount of messages required by the client. The battery exchange is the second most important factor, therefore an empirical study can check upon the time study for battery replacements. It thus seems that other input factors of the model are rather robust to variation.

WiFi has a smaller variation than cellular because its lifetime is higher than cellular to start with. Going from 8 to 10 replacements for example, will have a smaller impact on your lifetime than going from around 60 to 20. However, the WiFi option is, as already stated, not to be used since LoRa-private is available at a lower cost.

7.3 Use case 2: : Medication transport

7.3.1 Parameter set 1: 1 message, compression factor 1

The additional parameters of interest are shown in table 7.6.

TABLE 7.6: Additional SA input parameters use case 2

Parameter	Unit	Original value	Min	Mean	Max	Additional parameters	Distribution
Battery exchange	TMU	978,5	/	978,5	/	300	Maximum extreme distribution
LoRa subscription fee	/year	8	/	8	/	0,5	Normal
Amount of messages	Mes/day	1	/	/		/	Custom
Lifetime ratio LPWAN/cellular	[-]	5	/	5	/	Scale: 0,5	Maximum extreme distribution
Roaming addition	%	50	40	/	80	/	Custom

The same parameters and reasoning goes as in section 7.2. The only difference is the amount of messages per day, since the distribution here is custom where it was binomial before. Since in the port of Antwerp, it is more likely to receive alarm than during medication transport (stricter regulations), the input values here are lower. Values range from 1 message each 5 days to 2 messages per day.

7.3.2 Parameter set 2: 100 messages, compression factor 5

Table 7.7 shows the input for the second research parameter set.

TABLE 7.7: Use case 2, research 2: input parameters

Parameter	Unit	Original value	Min	Mean	Max	Additional parameters	Distribution
Battery exchange	TMU	978,5	/	978,5	/	300	Maximum extreme distribution
LoRa subscription fee	/year	8	/	6	/	0,75	Normal
Amount of messages	Mes/day	1	70	100	130	/	Uniform
Lifetime ratio LPWAN/cellular	[-]	40	/	40	/	Scale:2	Min extreme
Roaming addition	%	50	40	/	80	/	Custom

7.3.3 Results

7.3.3.1 Parameter set 1: 1 messages, compression factor 1

Results are shown in table 7.8 in thousands of euros.

TABLE 7.8: Output SA use case 2

Output chart						Most sensitive parameters	
Network	Minimum	Maximum	Mean	Std	Fitted distribution	Parameter	Percentage
Sigfox	176,75	186,38	179,15	0,87	Lognormal	Battery exchange	80
						Technical personnel	12,8
LoRa - Public	181,9	272,03	224,9	10,06	Normal	LoRa subscription fee	99,4
						Battery exchange	0,5
LoRa - Private	23235,75	144163,7	121071,9	9550,74	Minimum extreme	Rented location	99,9
						Economies of scale (2)	0,1
2G	159,78	219,86	185,34	11,69	Beta	Roaming addition	75
						Cellular subscription fee	24,3
4G	168,61	228,79	194,15	11,69	Beta	Roaming addition	75
						Cellular subscription fee	24,3
Irridium	8790,35	9893,58	9516,87	352,87	Minimum extreme	Satellite subscription fee	96,1
						Economies of scale (2)	3,6

Here cellular provides the best approach for the minimum. Its variation is high however, thus not being a safe choice of network. Again however, as the amount of messages increases, the costs increases with it. The roaming addition is responsible for a the largest portion of the variation. It thus might be advisable to omit roaming requirements and make each country self-provisioning. In this case, cellular will become competitive again since it will incline more to its minimum value.

LoRa private is much more expensive than the other available options. The influence of the "rented location" is very clear. The minimum fee per month can go to €55 with probabilities around 1%. It is clear that this possible drop of €20 per month has a significant effect on the output. Further investigation is advised for this parameter. Concrete price question for each use case might be necessary for concrete cost information.

LoRa public again requires more concrete information on the pricing of the subscription fee, it is again clear that pricings around €4.5 per year per end node makes it a competitive option.

For the satellite approach, again it is more expensive, which is mainly due to the subscription fee. This fee has a large influence on the result, but its pricing will not deviate up to a level where they are competitive with for example cellular.

7.3.3.2 Parameter set 2: 100 messages, compression factor 5

For cellular options, the impact of the frequency of battery replacements is very clear. As the amount of messages increases, the frequency goes up. This again confirms the requirement for more exact input in the amount of messages. It should be clear now that on the topic of battery replacement costs, user input (amount of messages) has a much higher impact than the modelling parameters (ratio 40 LPWAN over cellular, time of exchanging batteries, ...)

It also should be clear that the impact of roaming is less significant than the impact of the frequency of replacements when the amount of messages is high.

LoRa-private again only deviates because of the "rented location" pricing. More research is thus required, however it will never become a competitive option in this use case since its minimum value is still far above all other options their maximum.

Sigfox deviates with the amount of messages. However, its lifetime calculation is a good approximation, thus the deviation follows from the wide range in input values concerning the amount of messages (uniformly distribution from 70 to 130). The conclusion is that the Sigfox calculation is robust to the inputted values and variation originates from user input.

TABLE 7.9: Output SA use case 2, research 2

Output chart						Most sensitive parameters	
Network	Minimum	Maximum	Mean	Std	Fitted distribution	Parameter	Percentage
Sigfox	252,87	399,18	304,73	36,76	Pareto	Amount of messages	80,9
						Battery exchange	15,6
LoRa - Public	150,67	311,82	220,94	17,95	Lognormal	LoRa subscription fee	72,6
						Amount of messages	14,7
LoRa - Private	45844,15	142633,88	121077,54	9476,88	Minimum extreme	Rented Location	99,9
						Economies of scale (2)	0,1
2G	282,97	989,55	481,82	76,31	Gamma	Amount of messages	55
						Battery exchange	29,5
4G	291,88	998,31	490,62	76,31	Gamma	Amount of messages	55
						Battery exchange	29,5
Irridium	8921,24	10609,72	9815,28	359,49	Minimum extreme	Satellite subscription fee	92,7
						Amount of messages	4

7.4 Use case 3: Arrival times at De Lijn public transport

Since the end nodes are wired here, batteries don't have to be replaced. Therefore, the amount of messages per day does not influence the result, since its impact is on the frequency of replacements. Furthermore, the satellite solution is omitted since it is not cost effective and cellular networks are available. Therefore, there are no additional parameters in this use case.

7.4.1 Results

Results are shown in table 7.10 in thousands of euros.

TABLE 7.10: Output SA use case 3

Output chart						Most sensitive parameters	
Network	Minimum	Maximum	Mean	Std	Fitted distribution	Parameter	Percentage
Sigfox	386,64	386,86	386,73	0,04	Beta	Economies of scale	100
						/	/
LoRa - Public	230,51	346,54	289,77	13,03	Lognormal	LoRa subscription fee	100
						/	
LoRa - Private	569,56	4764,5	3916,83	359,75	Weibull	Owned location	99,7
						Technical personnel	0,2
2G	172,15	188,53	182,15	4,94	Minimum extreme	Cellular subscription fee	96,2
						Economies of scale (1)	3,8
4G	183,43	200,33	193,65	4,94	Minimum extreme	Cellular subscription fee	96,2
						Economies of scale (1)	3,8
BLE	17804,01	18645,99	18237,12	175,17	Triangular	Technical personnel	92,2
						Economies of scale (2)	7,8

The variation in Sigfox is very low since all of its inputs are fixed, except for the economies of scale percentage (1), which is applied after buying more than 100 pieces of an item. Since the only items bought for Sigfox are end nodes and batteries, its total effect is small, thus a small standard deviation.

The biggest uncertainty factor in LoRa private again is the monthly cost of a location. Here although there also is a small influence of the hourly cost of technical personnel. Thus in addition to more concrete pricing on location rental, investigation in personnel pricing is advised. Of course, seen the minimum which results from around €55 per month (already a very low cost), it is very likely that LoRa private will never be competitive to cellular.

Cellular already is the best option. It is clear however that the cost can further be lowered (although only a little) by hard pricing negotiations with Belgian telecommunication providers.

Bluetooth Low Energy has a very high installation cost, thus explaining the 99.2% influence of technical personnel. However its minimum value is still far above all other options and therefore should never be considered. Further investigation in its parameters is also not necessary.

7.5 Overall conclusion

The important factors to scrutinize in the future are different for the different networks. Furthermore, Sigfox seems to be fairly robust to changes in its input in comparison with other approaches.

7.5.1 WANs

On the topic of the parameters themselves, when the amount of messages is low (<10 per day), the deviation of costs for cellular technologies is mainly due to its subscription fee and roaming additions to it. When the amount of messages increases (> 50), the most important factor in the varition bcomes the amount of messages. This is because its cost implication is high. Namely, as the amount of messages grows, the frequency of replacements does so correspondingly. Thus for more accurate results, the subscription fee (as competitive as possible) and related roaming costs for that package have to be obtained from telecom vendors. Furthermore, when the amount of messages is high, it should be kept as low as possible, thus applying high compression ratios.

Sigfox is fairly robust to variations in user input. This is because there are no replacements at all over a lifetime of 10 years when the amount of messages is low. When the amount of messages is high, the replacements go up, but only by a small amount compared to cellular. Therefore, when there are battery replacements (and the amount of messages is thus high), the most important factor is not how many replacements there exactly are (since it is low anyways), but rather how much a replacement actually costs. This is the parameter "battery exchange" which is the time to exchange one single battery. Further (empirical) research is thus adivsed here.

The LoRa subscription fee is the most important factor with LoRa public. Pricings around €4.5 per year per device seem to be competitive. With LoRa-private, the most important factor is the cost of a rented location, when the amount of base stations is high (use case 2 and use case 3). Therefore, it should be reviewed if lower pricings are possible for this parameter. When the amount of base stations is low (use case 1), there is only small variation in LoRa private, and the discussion is similar to the one held for Sigfox in the previous paragraph.

Satellite variations are high simply because its initial input values are high. Relative to its original values, the deviations are small. It is not interesting to further scrutinize this in a sensitivity analysis because satellite would only be used when there is no other option, otherwise it will always be more expensive.

It should be clear that even though there is little information available on the ratio of lifetime (cellular vs LPWAN), and it is assumed 5 or 40, depending the amount of messages, its impact is very small. The user related input, the amount of messages has much higher impact. It should be stressed however that this is partly because battery replacement costs here were always low, because the transportation cost was never necessary. If this factor was included, the impact of battery replacement frequency (and thus also the ratio of lifetimes) would probably have been higher.

7.5.2 LANs

WiFi is very comparable to cellular on the topic of which parameters have the most impact. The sole difference is that WiFi has a higher CAPEX, because the network has to be installed. The impact of the economies of scale however (discount on large amount of routers) seems to be limited and the results are similar to cellular.

Zigbee and Z-Wave were not part of any sensitivity analysis here.

7.5.3 PANs

Bluetooth Low Energy does experience a very large impact from the economies of scale. Also from technical personnel. The hourly cost of technical personnel is important here because the beacons need their batteries replaced. Since the high amount of beacons, this cost is high. This would be the same for cellular end nodes, if travelling in between nodes were required. Therefore, it is useful to check if the €75 per hour can be lowered.

Furthermore, the economies of scale were important because the high amount of beacons. In general for all networks, it is advisable that if the amount of required items is very large, that a concrete tender is submitted to a company providing such items, and that there is a specific inquiry for a competitive discount seen the number of items bought. This can reduce uncertainties from this origin.

Appendix A

Amount of base stations: calculations

The surface is assumed rectangular. The amount of base stations is approximately equal to the total surface of the rectangle divided by the surface of one circle. One circle is of course the area covered by a single base station. Using this approximation, some of the area in between the circles will not be covered. The size of the area that is not covered depends of course on the size of the circles. The bigger the circles, the bigger the left out areas.

However, instead of a near full coverage, the applications here require full coverage of an area. The circles will thus overlap and one of the ways to this is by hexagonal packing. The hexagonal packing is also shown in figure 5.2.

The amount of base stations required in a hexagonal packing is simply the effective area covered by a circle, after subtracting overlaps. In figure A.1 this yellow area, framed rectangle ABCD.

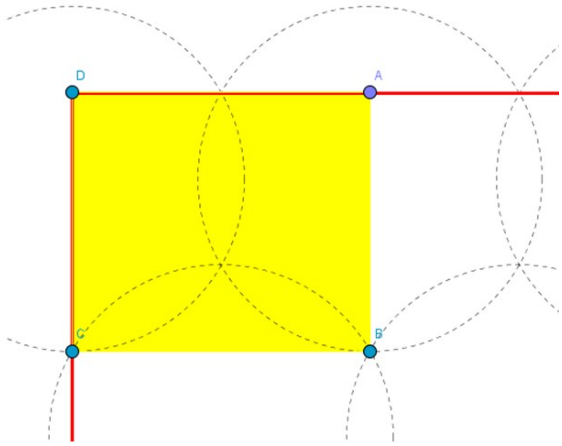

FIGURE A.1: Effective coverage of 1 circle

The amount of basestations thus can be calculated by dividing the total area by the area of the rectangle. In equation 5.3 the surface of the rectangle is given by user input. The denominator, the surface of rectangle ABCD can be calculated by multiplying its sides.

Due to symmetry, all angles formed by the blue lines in figure A.2 are equal, thus 60 degrees.

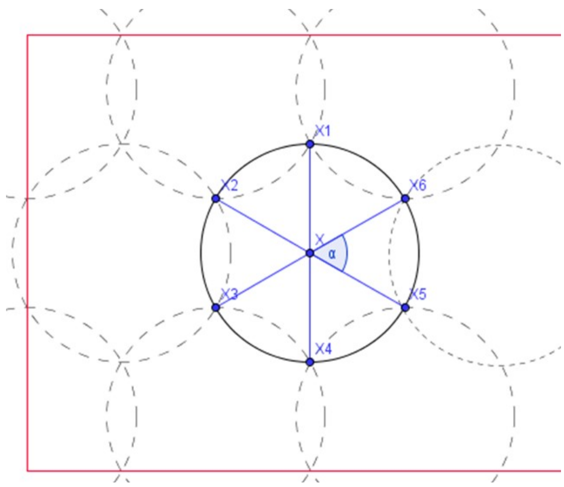

FIGURE A.2: Angles of the different circle sectors

Dividing this angle by 2, gives α in figure A.3. The radiuses of the circles are indicated by R. The sides of the rectangle are AD and DC.

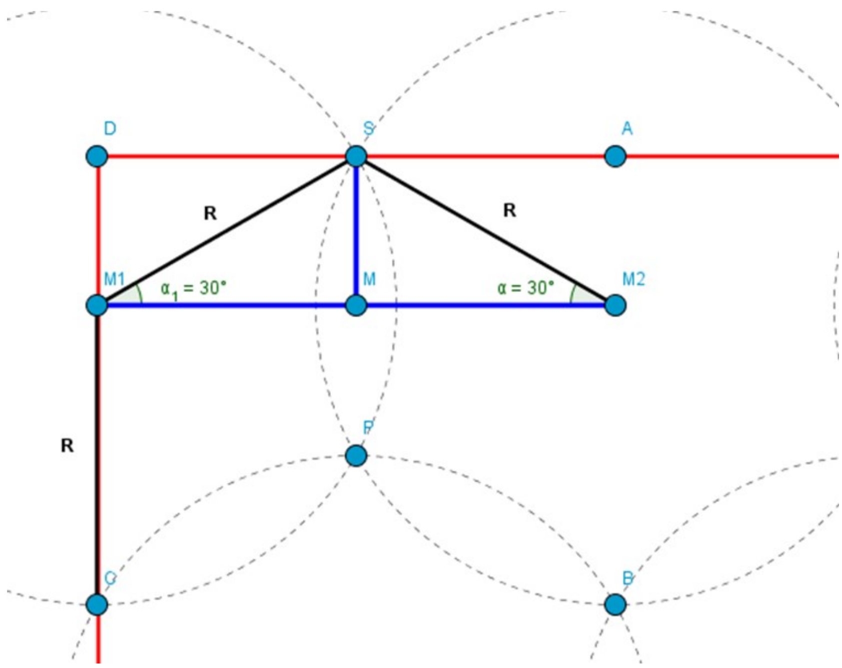

FIGURE A.3: Sides of the rectangle ABCD

The sides can also be written as in equation A.1.

$$|CD| = |SM| + R \tag{A.1}$$

$$|AD| = |M_1M_2| \tag{A.2}$$

Triangles SMM_1 and SMM_2 are both rectangular in M. Therefore equation A.3 applies.

$$R + |SM| = R + R\sin(\alpha) = R + R\sin(30°) = \frac{3R}{2} \tag{A.3}$$

$$|M_1M_2| = 2|MM_1| = 2R\cos(\alpha) = 2R\cos(30°) = \sqrt{3}R \tag{A.4}$$

The total surface of the rectangle ABCD in figure A.3 therefore is $\frac{3\sqrt{3}R^2}{2}$.

Appendix B

Subscription fee for public networks

B.1 Subscription fee information

Subscription fees can either be on a monthly or on a yearly basis. The subscription fees to all public networks are presented in the tables below.

Table B.1 shows the subscription fees on a yearly basis to Sigfox network per end node. These are obtained from industry experts, confirmed correct up to the first of March 2016.

Table B.1: Sigfox subscription fee

Subscription cost [€]/year		Amount of end nodes/communication chips					
Subscription level	Messages/day	<1000	<10000	<25000	<50000	<100000	<250000
Platinum	140	14	12	10	8	7	6
Gold	100	11	9	7	5,5	4	3
Silver	50	10	8	6	5	3,5	2
One	2	8	6	5	4	2,5	1,5

Table B.2 shows the subscription fees to the cellular network in Belgium. Equal pricing is assumed in neighbouring countries. Pricing is obtained from private tenders.

Table B.3 shows the monthly subscription fees to the satellite network of global operator Iridium. Pricings are obtained from their website. The values indicated green are official, others are assumed. Values in yellow are special discounts, assumed under train of thought "Economies of scale". These discounts in yellow are fairly large. In contrast, other values are all assumed and obtained by applying a 5% discount to the nearest

TABLE B.2: Cellular subscription fee

Subscription cost [€]/month	Amount of end nodes/communication chips				
Amount of MB/month	1	50	100	500	2000
1	0,35	0,34	0,33	0,32	0,32
2	0,6	0,58	0,57	0,55	0,54
5	1,1	1,07	1,05	1,01	0,99
10	2,5	2,43	2,38	2,3	2,25
20	3,75	3,64	3,56	3,45	3,38
50	4	3,88	3,8	3,68	3,6
100	4,5	4,37	4,28	4,14	4,05
250	6	5,82	5,7	5,52	5,4
500	12	11,64	11,4	11,04	10,8
1000	24	23,28	22,8	22,08	21,6
2000	40	38,8	38	36,8	36
5000	100	97	95	92	90

cell. Furthermore it should be noted that there is a subdivision in "cost/message" and an "activation fee". Up from the point of using 180 messages per month or more, it is cheaper to go with another formula, named "Go plus" instead of the "Go basic" formula. In the "Go plus" scenario the activation fee is higher, but the cost per message disappears. The calculation goes as in equation B.1.

$$\text{Total fee} = 181 \text{ messages} * \frac{€0.2375}{message} = €86.3275 > €86.32 \tag{B.1}$$

TABLE B.3: Satellite subscription fee

Subscription fee [€]/month		Amount of end nodes/transceivers		
Amount of messages/month		1	50	100
Price/message	<10	0,25	0,125	0,11875
	<180	0,2375	0,11875	0,1128125
	>180	Use Go plus instead of Go basic		
Activation fee/device/month	<10	45,41	22,70	21,57
	<100	43,34	21,57	20,49
	<180	86,32	43,16	41,00
	<1000	82,00	41,00	38,95
	>1000	77,90	38,95	37,00

Table B.4 shows the monthly subscription fees to the internet by the Belgian telecommunications provider Telenet. Pricings in green are again oficial, others are assumed. The yellow cells again have a fairly large discount to introduce economies of scale. Furthermore, it should be noticed that the pricings here are not based on the amount of end nodes, but rather on the amount of internet access points. It is possible to connect up to 4 router to a single internet access point, thereby reducing the costs.

TABLE B.4: WiFi subscription fee

Subscription cost [€]/month	Amount of Internet access points					
Amount of GB/month	1	100	1000	10000	100000	1000000
<100	27,5	11	10,45	9,9275	9,431125	8,95956875

B.2 Interesting notions

In table B.2, the amount of MB used per month per device will always be less than 1. Thus, usually only the first row applies to this paper.

In IoT, messages are sent in a data format. The data format will typically be only 4 or 5 characters. The first digit indicating what value is measured, the second being a space and the last two indicating a percentage value of the measured parameter by the sensor. These 4 characters are 1 message. 1 character can be represented by 1 byte and for each message there is an overhead of a message is 23 bytes Thus the amount of bytes per messages is roughly 27. This means that each Megabyte provides you with over 50000 of these messages, which is more than enough for one month for these applications.

When comparing tables B.1 and B.2, there is an interesting development in terms of subscription fees. Subtraction the cellular fees from the Sigfox fees gives the cost difference on a yearly basis, which is presented in table B.5.

TABLE B.5: Subscription fee comparison of Sigfox and cellular

yearly Sigfox fee - yearly cellular fee [€{}/device]						
Amount of Sigfox	Amount of chips					
messages	<1000	<10000	<25000	<50000	<100000	<250000
140	10,16	8,16	6,16	4,16	3,16	2,16
100	7,16	5,16	3,16	1,66	0,16	-0,84
50	6,16	4,16	2,16	1,16	-0,34	-1,84
2	4,16	2,16	1,16	0,16	-1,34	-2,34

The values indicated in green are when Cellular is more expensive, those in red indicate that Sigfox is more expensive. As the amount of messages increases, it becomes more and more important to take into account that cellular batteries drain more quickly. For this reason, cellular will supposedly be less expensive than Sigfox in the bottom left corner of the table, where the amount of messages is low and its subscription fee is lower than for Sigfox.

Bibliography

[1] N. Treloar. Video in the internet of things, 09-01-2014. URL http://www.ramp.com/media/video-in-the-internet-of-things/.

[2] Friis transmission equation, 24-03-2016. URL https://en.wikipedia.org/wiki/Friis_transmission_equation.

[3] Bluetooth, 25-05-2016. URL https://en.wikipedia.org/wiki/Bluetooth.

[4] Zigbee, 23-05-2016. URL https://en.wikipedia.org/wiki/ZigBee.

[5] ICP DAS CO. Home product solutions industrial wireless communication zigbee introduction, 2015. URL http://www.icpdas.com/root/product/solutions/industrial_wireless_communication/wireless_solutions/zigbee_introduction.html.

[6] Zigbee Alliance, 2016. URL http://www.zigbee.org/non-menu-pages/contact-us/.

[7] R. Viel. Lora technology, 2016. URL https://www.lora-alliance.org/What-Is-LoRa/Technology.

[8] Weightless SIG. N-wave deploys weightless-n smart city networks in denmark, 18-07-2015. URL http://www.weightless.org/news/nwave-deploys-weightlessn-smart-city-networks-in-denmark.

[9] Limére V. Methods engineering and work measurement, chapter 3: Work measurement, predetermined time systems, 2013.

[10] 2012. URL http://stackoverflow.com/questions/7716460/fully-cover-a-rectangle-with-minimum-amount-of-fixed-radius-circles.

[11] LinkLabs. Wifi vs. cellular: Differences uses for m2m applications, 13-11-2014. URL http://www.link-labs.com/wifi-vs-cellular-differences-for-m2m/.

[12] F. Pauls, S. Krone, W. Nitzold, G. Fettweis, and C. Flores. Evaluation of efficient modes of operation of gsm/gprs modules for m2m communications, 09-2013. URL http://ieeexplore.ieee.org/xpl/login.jsp?tp=&arnumber=6692200&url=http%3A%2F%2Fieeexplore.ieee.org%2Fiel7%2F6690585%2F6691970%2F06692200.pdf%3Farnumber%3D6692200.

[13] Texas Instruments. Cc1125: Ultra-high performance rf narrowband transceiver, 03-2012. URL http://www.alldatasheet.com/datasheet-pdf/pdf/454105/TI/CC1125.html.

[14] Amazon. Cloud storage pricing amazon simple storage service (s3), 2016. URL https://aws.amazon.com/s3/pricing/.

[15] 2016. URL https://www.schaefer-shop.be/shop/afzetsystemen/2,778,3290,10119802,0,0,,cc=A001629.

[16] Cloud storage pricing amazon simple storage service (s3), 24-04-2016. URL https://en.wikipedia.org/wiki/Sensitivity_analysis.