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Communication Protocols in Building Management Systems. State of the Art Assessment and the Future Influence of the Internet of Things.

- From the Perspective of a Global Lighting Enterprise.

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Communication Protocols in Building Management Systems. State of the Art Assessment and the Future Influence of the Internet of Things. - From the Perspective of a Global Lighting Enterprise.

Kommunikasjonsprotokoller i byggstyringssytemer. Analyse av nåværende status og virkningene fra Tingenes Internett. - Sett fra perspektivet til en global belysningsaktør.

"Which communication protocol is most likely to become leading in the light management systems in the professional building market in Europe during the next two till five years and which other communication protocols should the light management protocol be able to interoperate with?"

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Summary

The Internet of Things (IoT), which is about connecting things to the Internet so that the things can be a part of a bigger universe, learning from and to each other, is finding its way to the professional building segment imposing potentially endless new functionalities. But there is one significant obstacle that is limiting the true potential induced by the IoT - namely varying standards which prevent the devices and systems from communicating to each other. A communication protocol is a set of rules and formats that regulates the information exchange between the elements of a system and is the main actor in the standards war. The diverse and contradicting use of different protocols among industry actors and among different building projects is truly slowing down innovation and the transition towards the so-called "thinking buildings". This master's thesis aims to be a part of finding a solution to this problem by answering the research question: *"Which communication protocol is most likely to become leading in the light management systems in the professional building market in Europe during the next two till five years and which other communication protocols should the light management protocol be able to interoperate with?"*

The thesis uses the global lighting solution enterprise Glamox AS as case enterprise and complements this with a general literature review and a questionnaire study for finding data evidence. The methodology was both qualitative and quantitative and the data was analyzed through Porter's five forces, a simplified Cost-Benefit Analysis (CBA) and a Multi-Criteria Analysis (MCA). Seven sub-questions were constructed to make a more structured approach to answering the research question. The main findings of this thesis were found to be as follows:

The professional buildings are constantly changing and this thesis found that we have a transfer from intelligent to smart to thinking buildings which again can be characterized as a transfer from reactive to adaptive to predictive buildings. Building Management Systems (BMSs) were found to be an essential part of the transfer towards smart and thinking buildings and there were found to be a transition from the traditional way of operation where each technical system have their own IT structure to integrated solutions where the BMS, consisting of both software and hardware, is configured in a hierarchical manner. The transition was however found to be slow and often to originate from the lack of interoperability (the capability of different protocols to understand each other) between the different communication protocols. There was also found that BMSs are frequently divided into the field, automation and management level and that the Open Systems Interconnection (OSI) model is often used as a reference model when comparing and discussing different communication protocols.

There was performed a brief stakeholder analysis and a strategic analysis using the five force model of Porter to analyze the competitive situation for the Light Management System (LMS) segment of Glamox AS. The stakeholder analysis classified the identified stakeholders according to the Savage model and the most dangerous stakeholders were found to be the suppliers, the standardization organizations, the contractors and the shareholders. This is because these are the most likely stakeholders to change the potential for cooperation with Glamox - and turn to the "non-supportive" stakeholder category. The five force analysis found that the total competitive situation for Glamox was moderately in Glamox's disfavour. The main reason for this was found to be the bargaining power of suppliers, the threat of new entrants and the rivalry among the existing competitors. The most important factors in these negative forces were high bargaining power of suppliers of electrical (IoT) components and software, broadened product definition and the pressure from the new IoT products of the existing competitors. Two of the forces were found to be moderately in Glamox's favour. These forces were the "Bargaining Power of Buyers"-force and the "Threat of Substitute Products or Services"-force. The main positive factors in these forces were that increased product differentiation and closer customer relationship can reduce the bargaining power of the buyers and that the threat of substitute products or services might be reduced if continuing success of their LMS.

The literature review found that the communication protocols in a professional building should (1) be suitable for the size of the installation, (2) provide scalability of the network, (3) have the capability to interoperate with other devices and systems, (4) have sufficient range of communication, (5) have sufficient reliability and speed and minimal latency, (6) be secure, (7) have a competitive cost of installation and maintenance, (8) fit device management requirements and (9) be aligned with the industry trends. These nine characteristics were called success factors and were used in the MCAs which compared the three most probable scenarios constructed from the results of the questionnaire. The MCA had a strong conclusion, that Scenario 3, which uses Bluetooth Mesh at the field level and the TCP/IP suite with Wi-Fi at the physical layer at the automation and management level, was the best protocol stack for the office building used as reference. The non-monetary CBA compared the DALI and the Bluetooth Mesh protocol at the lighting field level for four different stakeholders and concluded that the Bluetooth Mesh protocol was most beneficial for Glamox, the building responsible and for the society and that the DALI protocol would be most beneficial for the users of the building. Since the Bluetooth Mesh protocol was found to be the best choice in the questionnaire, the CBA and the MCA, this thesis concluded that Bluetooth Mesh is the most likely communication protocol in LMSs in Europe during the next two till five years. The second part of the research question asks about which protocols the light management protocol should be able to interoperate with and the thesis concluded that the building specific protocols like KNX and BACnet and the current Internet protocol suite, based on the TCP/IP suite, is a poor fit with IoT applications and the future demands of BMSs and that it looks like we are moving towards a more IoT-suited protocol stack using protocols such as IEEE 802.15.4, 6LoWPAN, MQTT and UDP. Therefore, this thesis concluded that the light management protocol should be able to communicate with the future Internet protocol suite based on the transfer to IPv6.

Key Words: Smart Building, Thinking Building, Building Management Systems, Building Automation Systems, Light Management Systems, Communication Protocols, Standardization, Interoperability, Field Level, Automation Level, Management Level, OSI Model, BACnet, KNX, Radio Frequency, Bluetooth, Mesh, TCP/IP, Wi-Fi, Ethernet, DALI, IEEE 802.15.4, MQTT, UDP, IPv6, 6LoWPAN, Glamox AS

Sammendrag

Tingenes Internett, som handler om å koble ting til Internett, slik at tingene kan være en del av et større univers og lære fra og til hverandre, har funnet sin vei inn i det profesjonelle byggsegmentet og kan gi opphav til et potensielt uendelig antall nye funksjoner. Men det er et betydelig hinder som begrenser det virkelige potensialet som Tingenes Internett fremkaller - nemlig varierende standarder som forhindrer enhetene og systemene i å kommunisere med hverandre. En kommunikasjonsprotokoll er et sett med regler og formater som regulerer informasjonsutvekslingen mellom elementene i et system og er hovedaktør i standardkrigen. Den mangfoldige og motstridende bruken av ulike protokoller blant industriaktører og blant ulike byggeprosjekter, reduserer innovasjonspotensialet og sakner overgangen til såkalte "tenkende hus". Denne masteroppgaven tar sikte på å bidra til å finne en løsning på dette problemet ved å svare på forskningsspørsmålet: *"Hvilken kommunikasjonsprotokoll er mest sannsynlig å bli ledende i lysstyringssystemer på det profesjonelle byggmarkedet i Europa de neste to til fem årene, og hvilke andre kommunikasjonsprotokoller bør lysstyringsprotokollen kunne interoperere med?"*

Denne avhandlingen bruker den globale belysningsvirksomheten Glamox AS som casestudie og komplementerer dette med et generelt litteraturstudie og en spørreundersøkelse for å finne databevis. Avhandlingens metodikk er både kvalitativ og kvantitativ, og datagrunnlaget ble analysert gjennom Porters femkraftsmodell, en forenklet kost-nytte analyse og en multikriterieanalyse. Syv delspørsmål ble konstruert for å bidra til en mer strukturert prosess til å svare på forskningsspørsmålet. Hovedfunnene i denne avhandlingen ble funnet å være som følger:

Profesjonelle bygg er i konstant endring og avhandlingen fastslo at vi har en overgang fra intelligent til smart til tenkende, en overgang som kan bli karakterisert som en overgang fra reaktiv til adaptiv til prediktiv. Byggstyringssytemer ble funnet å være en viktig del av overgangen til smarte- og tenkende bygg og det ble funnet et skifte fra den tradisjonelle driften der hvert teknisk system har sin egen IT-struktur til integrerte løsninger der byggstyringssytemet, som består av både programvare og maskinvare, er konfigurert på en hierarkisk måte. Overgangen ble imidlertid funnet å være langsom, noe som ofte stammer fra mangelen på interoperabilitet (evnen forskjellige protokoller har til å forstå hverandre og samhandle) mellom de ulike kommunikasjonsprotokollene. Det ble også funnet at byggstyringssytemer ofte deles inn i felt-, automatiserings- og styringsnivå, og at OSI-modellen ofte brukes som referansemodell når man sammenligner og diskuterer ulike kommunikasjonsprotokoller.

Det ble utført en enkel interessentanalyse og en strategisk analyse ved hjelp av Porters femkraftsmodell for å analysere konkurransesituasjonen for Glamox's lysstyringssegment. Interessentanalysen klassifiserte interessentene i henhold til Savage-modellen, og de mest truende interessentene ble funnet å være leverandørene, standardiseringsorganisasjonene, entreprenørene og aksjonærene. Dette skyldes at disse er de mest sannsynlige interessentene til å bevege seg i en retning av mindre grad av samarbeid med Glamox - og å dermed inntre i den "ikke-støttende" interessentkategorien. Femkraftsanalysen fant at den totale konkurransesituasjonen for Glamox var moderat i Glamox's disfavør. Hovedårsaken for dette ble funnet å være forhandlingsstyrken til leverandører, trusselen fra nye aktører og rivaliteten blant eksisterende konkurrenter. De viktigste faktorene i disse negative kreftene var høy forhandlingsmakt hos leverandører av elektriske komponenter og programvare, utvidet produktdefinisjon og presset fra de eksisterende konkurrentene fra deres nye Tingenes Internett-produkt. To av kreftene ble funnet å være moderat i Glamox's favør. Disse kreftene var forhandlingsstyrken til kjøpere og trusselen fra substituttprodukter eller tjenester. De viktigste positive faktorene i disse styrkene var at økt produktdifferensiering og tettere kundeforhold kan redusere forhandlingskapasiteten til kjøperne og at trusselen fra substituttprodukter eller tjenester kan bli redusert hvis lysstyringssystemets suksess fortsetter.

Litteraturstudiet fant at kommunikasjonsprotokollene i et profesjonell bygg burde (1) være egnet for installasjonens størrelse, (2) gi skalerbarhet av nettverket, (3) ha evne til å interoperere med andre enheter og systemer, (4)) ha et tilstrekkelig kommunikasjonsområde, (5) ha tilstrekkelig pålitelighet og hastighet og minimal forsinkelse, (6) være sikker, (7) ha en konkurransedyktig kostnad for installasjon og vedlikehold, (8) passe med kravene til styring av enhetene og (9) være i overenstemmelse med bransjens trender. Disse ni egenskapene ble kalt suksessfaktorer og ble brukt i multikriterieanalysen som sammenlignet de tre mest sannsynlige scenariene fra spørreundersøkelsens resultater. Multikriterieanalysen hadde en sterk konklusjon, at Scenario 3, som bruker Bluetooth Mesh på feltnivå og TCP/IP-pakken med Wi-Fi i det fysiske laget på automatiserings- og styringsnivå, var den beste protokollkombinasjonen for kontorbygget som ble brukt som referanse. Den ikke-monetære kost-nytte analysen sammenlignet DALI- og Bluetooth Mesh-protokollen på belysningsfeltnivået for fire ulike interessenter, og konkluderte med at Bluetooth Mesh-protokollen var mest fordelaktig for Glamox, byggansvarlig og for samfunnet, og at DALI-protokollen ville være mest gunstig for brukerne av bygningen. Siden Bluetooth Mesh-protokollen ble funnet å være det beste valget ifølge spørreundersøkelsen, kost-nytte analysen og multikriterieanalysen, konkluderte denne avhandlingen at Bluetooth Mesh er den mest sannsynlige kommunikasjonsprotokollen i lysstyringssystemer i Europa de neste to til fem årene. Den andre delen av forskningsspørsmålet spør om hvilke protokoller lysstyringsprotokollen burde kunne interoperere med og avhandlingen konkluderte med at de byggspesifikke protokollene som KNX og BACnet og de nåværende Internettprotokollene, basert på TCP/IP-pakken, er lite passende for Tingenes Internett-applikasjoner og fremtidige krav til byggstyringssytemer, og at det ser ut til at vi beveger oss mot en mer Tingenes Internett-egnet protokollkombinasjon, bestående av protokoller som IEEE 802.15.4, 6LoWPAN, MQTT og UDP. Derfor konkluderte denne oppgaven at lysstyringsprotokollen burde kunne kommunisere med de fremtidige internettprotokollene, basert på overføringen til IPv6.

Nøkkelord: Smarte bygg, Tenkende bygg, Byggstyringssystemer, Byggautomatiseringssytemer, Lysstyringssytemer, Kommunikasjonsprotokoller, Standardisering, Interoperabilitet, Feltnivå, Automatiseringsnivå, Styringsnivå, OSI-modell, BACnet, KNX, Radiofrekvens, Blåtann, Mesh, TCP/IP, Wi-Fi, Ethernet, DALI, IEEE 802.15.4, MQTT, UDP, IPv6, 6LoWPAN, Glamox AS

Preface

This master's thesis is written in cooperation with Glamox AS and the Department of Mechanical and Industrial Engineering at NTNU during spring 2018. The thesis summarizes the work done in the subject "TPK4920 - Project and Quality Management, Master's Thesis" and accounts for 30 credits. This master's thesis is a compulsory and final activity as part of accomplishing the degree Master of Science in Mechanical Engineering and a continuation of the report written in the subject "TPK4520 - Project and Quality Management, Specialization Project" during autumn 2017.

The main focus of this master's thesis is communication protocols in building management systems and is thus a pretty specific and technical area of study. Throughout this thesis, relevant concepts and terms will be explained in such a way that a reader with little or none knowledge of the main concepts will find the content understandable to some degree. Readers with education or working disciplines within the construction industry, building management systems, information and communication technologies, the professional lighting industry or similar fields will benefit the most of this report.

This work has been fulfilling, exciting and challenging. The themes of this thesis belong to a rapidly changing environment and it is not clear how the future BMSs will be structured. Because of this, I have had the possibility to gain a deep insight about technologies that are going to form future buildings and get competence that is much needed in Norwegian as well as worldwide business and industry. The most challenging part of the writing process has been to decide what was a suitable degree of explanation of the different concepts and to extract information about topics that are greatly biased by the organizations supporting the technology at question.

I want to thank the employees in Glamox AS who agreed to participate in interviews and open-ended conversations during the writing period and thus sharing their opinions and viewpoints regarding the evolving trends in the lighting industry. I will also thank Glamox AS for providing office space during the writing period and for giving me the opportunity to visit the trade fair in Frankfurt. Additionally, I would like to express gratitude to all the respondents of the questionnaire.

My supervisory team, consisting of Dr Bjørn Andersen at NTNU and Laboratory Manager Geir Sylte at Glamox AS has been essential in this thesis work. Bjørn has contributed to ensuring "project- and quality management"-focus of the thesis and given constructive feedback on the drafts. Geir has been a conversation partner in all the important decision making phases and his technical knowledge have been crucial. Both of you have answered all my questions with enthusiasm and positivity and deserves my greatest thanks.

Molde, June 8th, 2018

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Abbreviations and Acronyms

6LoWPAN	IPv6 Low Power Wireless Personal Area Network
AC	Alternating Current
API	Application Programming Interface
BA	Building Automation
BLE	Bluetooth Low Energy
BMS	Building Management System
BR	Building Responsible
CBA	Cost-Benefit Analysis
CoAP	Constrained Application Protocol
DALI	Digital Addressable Lighting Interface
DDC	Direct Digital Control
GUI	Graphical User Interface
HCL	Human Centric Lighting
HTTP	HyperText Transport Protocol
HVAC	Heating, Ventilation and Air Conditioning
IB	Intelligent Building
IEEE	Institute of Electrical and Electronics Engineers

IoT	Internet of Things
IP	Internet Protocol
ISO	International Organization for Standardization
IT	Information Technology
LED	Light-Emitting Diode
LMS	Light Management System
MAC	Media Access Control
MCA	Multi-Criteria Analysis
MQTT	Message Queuing Telemetry Transport
OSI	Open Systems Interconnection
PBS	Professional Building Solutions
PLC	Programmable Logic Unit
QFD	Quality Function Deployment
RF	Radio Frequency
RQ	Research Question
RTU	Remote Terminal Unit
SIG	Special Interest Group
SQ	Sub-Question
TCP	Transmission Control Protocol
TP	Twisted Pair
UDP	User Datagram Protocol
Wi-Fi	Wireless Fidelity

Chapter 1

Introduction

This chapter sets the settings of this master's thesis. Firstly, a justification of the chosen theme of this thesis will be given. Secondly, the Research Question (RQ) will be presented followed by the scope of this wide and still developing field. The general limitations will also be presented. Lastly, the structure of this master's thesis will be given.

1.1 Background

The Internet of Things (IoT), Big Data, Machine Learning, Artificial Intelligence, Virtual Reality. The list goes on and on. Top buzzwords in today's digital society. It is all about connecting "things" to the Internet so that the "things" can be part of a bigger universe learning from and to each other. But have we really unlocked the true potential of the IoT? No. We are in fact far from truly utilizing its potential value, which according to McKinsey Global Institute (2015) can represent as much as 11 % of the entire world economy by 2025. This master's thesis regards one of the identified obstacles to the "IoT promised land" as Silvair (2018) calls it, namely, varying standards which prevents devises and systems from communicating to each other. The IoT we experience today is heavily fragmented and lacks interoperability. Achieving interoperability, which means that the different devices of a system can understand each other and communicate, is predicted to capture roughly 40 %, and in some cases as much as 60 %, of the potential value across IoT applications (McKinsey Global Institute, 2015).

The situation we see with the IoT today, where a number of different technologies and protocols are coexisting and no one really knows what to settle for, mirrors the challenges faced by the technology industry in the early days of the Internet. According to Silvair (2018) a number of competing protocols proliferated back then, including IBM's SNA, Xerox' XNS, Novell's IPX/SPX, Apple's AppleTalk and many others, but it was TCP/IP that emerged as the protocol of choice for most networking applications, eventually becoming basically synonymous with the technical definition of the Internet. There is no doubt that without agreed-upon protocols and standards, the Internet and the World Wide Web would not have become what it is today. There are currently a two-digit number of communication protocols used in IoT applications, each protocol limiting the market penetration of the other. Fortunately, technological specialists all agree that there must be a transfer to more standardized use of open protocols leading to a universal IoT communication protocol stack. The big problem is, however, that no one has the guts to point out the winning horse, at present time.

This master's thesis focuses on communication protocols in the professional building sector which is used in Building Management Systems (BMSs). According to Feder (2018), the IoT is a true game changer in building automation and building management. Merging all the technical systems together in one common interface is the main issue in building management today. The specialized technological actors like HVAC or lighting enterprises have traditionally had their own management systems and merging these together is found to be a huge challenge. Why is this? Kejriwal and Mahajan (2016) wrote that the IoT applications must bring together many diverse types of data from many different sources to achieve a fully integrated BMS with all of its premises for increased efficiency. They also stated that the dynamic and continuously evolving IoT technology presents ongoing challenges: "For instance, a lack of industry standards and benchmarks hampers communication among different competing and legacy IT [Information Technology] systems. Many of the individual BMS use their own standards leading to multiple protocols; in a 2014 survey, for almost half of respondents, 50 percent of their building retrofit projects involve multiple protocols that do not communicate with each other" (Kejriwal and Mahajan, 2016). System integration is often of low priority as companies, particularly at the building design phase often emphasize lowering initial costs over collaboration (Kejriwal and Mahajan, 2016).

In the professional building segment, there is a tendency towards "Smart Buildings". Benefits such as improved energy efficiency, optimal area usage, less waste etc. have been proven to be inherent characteristics of a functioning smart building. But there are several obstacles to overcome. The Norwegian magazine "Teknisk Ukeblad" dedicated their March number to the smart building theme. Here it is stated that the Norwegian building industry itself is slowing down the implementation and that "stupid quotation prices" ("dumme anbud") are too often the quotation that wins the project (Teknisk Ukeblad, 2018). These are quotation prices offering simple/old technologies, limiting the implementation of new, potentially revolutionizing solutions. This thesis is written in cooperation with Glamox AS, a global lighting enterprise operating, among others, in the professional building market. In an interview from 2017, CEO of Glamox expressed that in the aftermath of the Light-Emitting Diode (LED) transitions, they see a whole range of new opportunities appearing as different technologies converge into new lighting applications and services. "Connectivity, Light Management Systems, Internet of Things are buzz words today, but they will change our lives and the industry in the future" (Arc Magazine, 2017). Chemel (2015) stated that the LED revolution may be over but the story of intelligent lighting is just beginning:

"Who will win? As software eats the lighting market as inexorably as it has consumed so many others, the winners will be those companies that recognize this shift early and adapt their offerings to take advantage of it. Companies who integrate sensing, networking and control into software-based platforms will lead the way; those who remain exclusively focused on hardware do so at their own risk" (Chemel, 2015).

So which of the available communication protocols is most reliable? Which offers the most for manufacturers of smart products, and has the greatest potential to survive the standards war, eventually becoming the go-to technology to connect the IoT? What are the most important factors to succeed in this environment? How large is really the problem of interoperability? These are some of the questions that will be attempted answered throughout this thesis.

1.2 Research Question

This title of this master's thesis is: "*Communication Protocols in Building Management Systems. State of the Art Assessment and the Future Influence of the Internet of Things. - From the Perspective of a Global Lighting Enterprise.*" This title is both wide and specific at the same time. Communication protocols is a quite specific and technical area of investigation while BMSs and the IoT embraces a range of different themes and applications. Using the perspective of a global lighting enterprise gives the thesis a more solid ground. The title of this thesis is of course based on an RQ. The RQ which will be aimed answered in this master's thesis is as follows:

"Which communication protocol is most likely to become leading in the light management systems in the professional building market in Europe during the next two till five years and which other communication protocols should the light management protocol be able to interoperate with?"

With an aim to ease the research process and make a structured approach to answering the RQ, several Sub-Questions (SQs) were constructed. These SQs will be answered throughout this report, and the aggregated sum of these answers will be the basis of the final conclusion. The SQs are as follows:

(a) Which trends are emerging in the building and BMS landscape?

(b) What is interoperability and why is it important?

(c) What is the current competitive situation for Glamox AS in the IoT environment?

(d) What are the main differences between wired and wireless protocols?

(e) Why is not "the Internet" used at all the levels of building management?

(f) What is critical success factors for communication protocols used in building management?

(g) Which light management protocol is most beneficial?

Cameron and Price (2009) emphasize that the RQ should be divided into SQs/objectives who communicates the details of the research and what is intended to be done. This is also the purpose of the SQs in this report. The RQ and the SQs include several terms and concepts that need to be further explained and put in context. In the next sub-chapter, the system boundaries and the scope of this thesis will be put in place.

1.3 Scope and Limitations

The main scope of this master's thesis is communication protocols used in professional buildings and the future protocols flourished by the increasing number of connected devices. In this sub-chapter, more specifics regarding the scope and why the system boundaries are sat as they are will be presented. The most general limitations will also be expressed.

The future is quantified to two till five years in the RQ. The reason for this narrow time span is because the scope of this thesis is highly evolving. No one would have known what to answer to the questionnaire questions if it were asking about the probable protocols in 2030 and the conclusion would have been less solid. There is also worth mentioning in this regard that people tend to overestimate the change that will occur in the next two years and underestimate the change that will occur in the next ten (Gates, 1995). This fact has been taken into account when analyzing the answers to the questionnaire and the general theoretical evidence.

Regarding the case enterprise, Glamox AS, only their Professional Building Solutions (PBS) division will be at focus (neglecting marine and offshore markets). The geographical scope is set to Europe and mainly Northern Europe. This is because this is the main geographical market of the PBS division of Glamox and because most of the respondents of the questionnaire operate in the European continent.

When it comes to technology developments there is assumed that technologies currently used are expected to persist through the forecast period (next two till five years) and that the technology developments will continue in the same pace as today.

The main limitations of this thesis are as follows:

- Lack of market report data which led to high reliance on the questionnaire.
- Largely evolving area of investigation which made it impossible to keep up with the various expert opinions during the writing process.
- Information regarding the respective protocols, general BMS architecture and the use of technologies can be largely biased of the mother organization, monetary incentives and similar.

Specific limitations for the various methods used in the thesis will be given in the respective methodology sub-chapters.

1.4 Structure of Thesis

The subsequent chapters of this thesis are structured as follows: Chapter 2 presents the methodology of this thesis and explains why things were done as they were. The methodology is divided into four main parts, the research design, the data collection methods, the data analysis methods and lastly, the quality assessment.

Chapter 3, the Theory, presents the important concepts and terms of this thesis. Readers with a solid pre-knowledge regarding the technical aspects of BMSs and communication protocols will probably already be familiar with the content of this chapter.

Chapter 4 is the Case chapter. In this chapter, the reader will be introduced to Glamox AS and their current Light Management System (LMS) will be presented. The competitive situation for Glamox will also be analyzed.

Chapter 5 is the Analysis chapter and analyzes important considerations when selecting a communication protocol for smart building usage. The results of the questionnaire are analyzed and illustrated in this chapter. This chapter also performs a simplified Cost-Benefit Analysis (CBA) and a Multi-Criteria Analysis (MCA).

Chapter 6, the Conclusion, states the main findings, gives explicit answers to the SQs, and most importantly, establishes a final conclusion. This chapter will also comment the research design of the thesis and present some possible directions for further work.

The last part of this thesis consists of a full biography and appendices. When speaking about the structure of the thesis, the researcher will like to emphasize that this thesis has been constructed as clear and logical as possible and that all relevant links and cross-referencing is clickable, easing the reading process when reading the thesis digitally.

Chapter 2

Methodology

A method can be defined as "A particular procedure for accomplishing or approaching something, especially a systematic or established one" while a methodology is defined as "A system of methods used in a particular area of study or activity" (Oxford Dictionary of English, 2018). The purpose of this chapter is to explain what, why, how and when the different parts of this research were done.

As will come evident in the following sub-chapters, this research uses a mixed-methods approach. This can be called methodical triangulation, which involves the use of multiple methods in that a range of different means of data-gathering is utilized (Cameron and Price, 2009). Using several methods to build up the theory and the basis of the analysis increases the reliability of the research.

2.1 Research Design

Figure 2.1 illustrates the research process of this study. The process is divided into three main phases and has an additional Phase 0 for preliminary research.

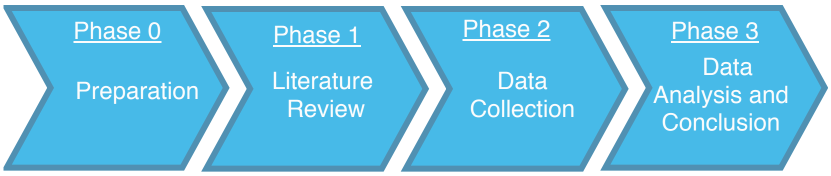

Figure 2.1: Research process

Phase 0 was concerned about preparing for the main work with the aim to specify the theme of the research. To find possible directions several factors were evaluated like the degree of future relevance in the technical environment, the research potential and last but not least Glamox's corporate interest. In the preparation phase, a large number of articles were read and several conversations with relevant Glamox employees were conducted. The starting point for the RQ was formulated after Phase 0. When formulating a researchable problem, there are several crucial features to consider, as described by Walliman (2010). The RQ should be: Stated clearly and concisely, significant (i.e. not trivial or a repeat of previous work), delineated (in order to limit its scope to practical investigation), possible to obtain the information required to explore the problem and possible to draw conclusions related to the problem (Walliman, 2010). These factors were taken into account when formulating the RQ given in Sub-Chapter 1.2. Phase 1 was about conducting the literature review. This process will be described in Sub-Chapter 2.2.1 of this report. Phase 2 is the data collection phase and concerns the process of extracting and formulating the written evidence. Phase 1 and 2 was to a large extent performed simultaneously. An important part of both these phases was to combine the primary and secondary data material into logical chapters and sections. The last phase was about analyzing the data and establishing the final conclusion.

2.1.1 Research Purpose

According to Cameron and Price (2009) establishing a clear purpose is perhaps the most important thing to do in a research since it will determine the subsequent choices because everything done subsequently should be designed to achieve the purpose. The purpose of this thesis is to investigate what is the status quo, find out why it is so and find the most likely way ahead. Based on this, one can characterize the purpose of this research as explanatory. Explanatory research aims to identify and explain relationships of the things being researched (Cameron and Price, 2009).

2.1.2 Qualitative and Quantitative Methods

Data can be divided into two categories depending on their characteristics i.e. whether they can be reduced to numbers or presented only in words. According to Walliman (2010), qualitative research depends on careful definition of the meaning of words, the development of concepts and variables, and the plotting of interrelationships between these. Since this research is situated around theory, concepts and a case study, the qualitative method has been an important research method for this research. Quantitative method, on the other hand, is situated around gathering quantified data (i.e. data in measurable/quantifiable units) (Walliman, 2010). Expressing quantifiable data do not mean that the quantitative method has been used. It is the collection phase that is essential. The questionnaire of this thesis is constructed to get quantifiable data, meaning that it belongs to the quantitative method category. The CBA and the MCA is also part of the quantitative method category.

2.1.3 Reasoning Technique

Walliman (2010) stated that inductive reasoning starts from specific observations or sensory experiences and then develops a general conclusion from them, as opposed to deductive reasoning who begins with general statements (premises) and, through logical argument, comes to a specific conclusion. A combination of both inductive and deductive reasoning has been used in this research but the inductive approach, which is generally best suited for qualitative research, is the most used approach. Walliman (2010) further claimed that it is the combination of experience with deductive and inductive reasoning which is the foundation of modern scientific research.

Deductive research goes from the general to the more specific (Sekaran and Bougie, 2016). This research as a whole can be classified as deductive. It starts out with general theory about technical terms and the communication protocols which is then compared to Glamox and the general building industry and the quantitative data from the questionnaire. Combining it all together through various types of analysis methods leads to the final answer to the RQ.

2.1.4 Time Span and Time Horizon

Figure 2.2 below, presents the timeline of this master's thesis' writing process. The circles show important milestones and the dotted rectangles describes what chapters were written in the given month and/or the main focus of the month. This thesis has a time span of exactly 20 weeks, from the 15th of January to the 11th of June 2018. The RQ was specified early in the research process, on the 18th of January. Since the main theme of the thesis, communication protocols, was rather new for the researcher, most of January and February were used to collect information about such themes and writing the theory part of this thesis. March was mainly devoted to the questionnaire and the trade fair in Frankfurt and writing the main content for Chapter 2 and 4. In April the analysis of the thesis was performed and in May the conclusion was written, along with making some adjustments in Chapter 1-5. One more formal conversation with the supervisor at Glamox was also performed during May and the results of the analysis were reviewed and adjusted based on comments from the supervisors. The available time in June was used to proofreading.

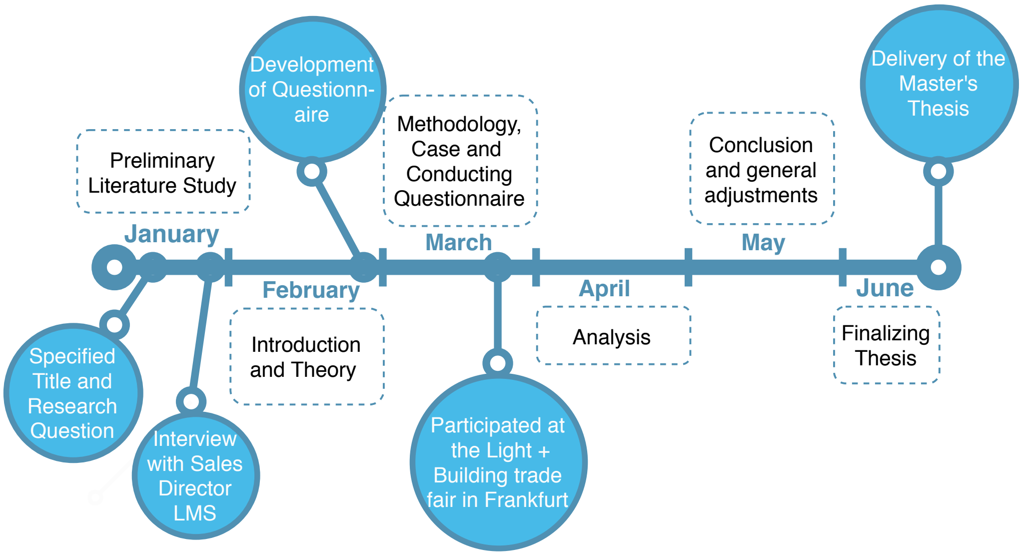

Figure 2.2: Timeline of the thesis work

The two main time horizons in research are: longitudinal and cross-sectional. Longitudinal studies trace developments over time while cross-sectional studies take a "picture" of a specific moment in time (Walliman, 2010). The literature review is mainly based on secondary data where the data have been collected over a (long) period of time and is thus a longitudinal study. The case study and the analysis are based on an interview, conversations, a questionnaire and the current status of the professional building landscape and are thus cross-sectional. Based on this, one can say that both time horizons have been used in this research and that, because of the heavy focus on the currently developing trends in building automation, the cross-sectional study has been the most important time horizon.

The main limitation regarding the time span is that this report covers a broad thematic area and that the 20 weeks available did not give the researcher the possibility to dig deep into details. Another limitation regards the unforeseeable future. Since IoT, building automation and the preferences of the leading industry actors are living in a rapidly changing environment, there is a possibility that this research will be outdated shortly after submission.

2.1.5 Case Study - Glamox AS

This master's thesis is designed around the enterprise Glamox AS and the researcher cooperated mainly with the Laboratory Manager in Molde, Geir Sylte, who also is the supervisor from the industry in this master's thesis. Glamox was chosen as case enterprise because they are operating in the professional lighting industry and are thus an important actor in the BMS landscape. There is also no doubt that the IoT is having a large impact on the professional lighting industry and that it is important for Glamox to keep up with the changing competition and customer demands induced by the IoT. Glamox was also chosen because the researcher was familiar with this enterprise from writing the project thesis during the autumn 2017 and because Glamox was eager to continue the collaboration. Getting an outside perspective on the status quo can be helpful to any enterprise and Glamox has taken an important step towards gaining more knowledge regarding whom they are in the BMS context by agreeing to the conduction of this research.

Cameron and Price (2009) stated that case study research is often wrongly described as a research "method". They further explain that a case study is a research strategy, an approach to research to be designed, and which uses a range of research methods (secondary-data methods included) and analyses in an attempt to answer the RQ. Eisenhardt (1989) stated that case studies can involve either single or multiple cases, and that case studies typically combine data collection methods such as archives, interviews, questionnaires and observations. This case study uses three methods, literature review, interview and questionnaire for data collection and one data analysis method. The literature review was used to find relevant qualitative and quantitative data regarding Glamox and Glamox's solutions and the interview was used to collect primary data and get insights about general opinions and future trends. Short conversations or approaching the responsible Glamox employee with a single question was an important way to find specific case data about for instance technological solutions. The questionnaire was used to find a general perspective of protocols in light and building management and the data analysis method was used to evaluate the competitive landscape. Combining all of these methods gave a solid base of knowledge regarding the case enterprise and the outside factors.

General limitations of a case study approach are according to Cameron and Price (2009): (1) The "embeddedness" of the problem can make it difficult to clearly define what should and what should not be included. (2) The use of multiple sources of data and multiple methods of data-gathering makes the process very time-consuming. (3) The use of multiple methods requires a wider analytical skill set. (4) The researcher has to be sure that he or she can synthesize the research findings to present a coherent set of conclusions. Since the researcher was familiar with the methodology used in this case study these limitations were not found to dominate. More specific limitations of this case study are the rapidly changing environment and the different preferences among the professionals.

As previously stated three methods for data collection were used in the case study. These three methods were of course also used to get insights beyond Glamox, meaning general insights about communication protocols in the BMS landscape. In the following sub-chapter, the data collection methods of this thesis work will be described.

2.2 Data Collection

"Data come in two main forms, depending on its closeness to the event recorded. Data that has been observed, experienced or recorded close to the event are the nearest one can get to the truth, and are called primary data. Written sources that interpret or record primary data are called secondary sources, which tend to be less reliable" (Walliman, 2010, p. 69).

Both primary and secondary data have been important in this research. The data extracted from the literature review is mainly secondary data coming from different sources ranging from academic publications to consultant reports and general websites. The basis for the analysis of this thesis is the secondary data from the literature review and the primary data from the semi-structured interview, conversations and questionnaire. The data collection of this thesis can be divided into three distinct parts or methods, literature review, interview and questionnaire. These methods will be thoroughly described in the following sub-chapters.

2.2.1 Literature Review

According to University of Wisconsin-Madison (2018), the purpose of a literature review is to "analyze critically a segment of a published body of knowledge through summary, classification, and comparison of prior research studies, reviews of literature, and theoretical articles". The format of a literature review may vary from discipline to discipline and may be a self-contained unit, an end in itself or a preface to and rationale for engaging in primary research. In theses and dissertations the literature review is often an own chapter. (University of Wisconsin-Madison, 2018)

The content abstracted from the literature review of this thesis is mainly put in the theory chapter. There is, however, pieces from the literature review all over this thesis. For the purpose of this research, it was found most applicable to do a general literature review without setting any rules or restrictions for following a specific procedure or similar. However, the screening of the material was on a general basis evaluated according to the procedure given in the flowchart in Appendix A. As can be seen from the flowchart, Oria (The Digital Library Database to NTNU), Google Scholar and the general World Wide Web (Google) was used as search engines. There was also conducted searches in academic databases such as Institute of Electrical and Electronics Engineers (IEEE) Xplore, Web of Science and Scopus without much success. The following bullet point list shows the most used keywords in the literature review. The keywords were used alone and in different combinations. "*" means with and without "s". The list is not complete.

- "Building Management System*" OR BMS
- "Building Automation" OR BA
- ("Communication Protocol*") AND BMS
- "Wireless Communication Protocol*"
- "OSI model"
- (Layers OR Levels) AND (Building Management System*)
- ("Lighting Protocol*") OR ("Lighting Communication Protocol*")
- Interoperability AND (Communication Protocols)

There was also conducted more specific searches for finding definitions and other important theoretical descriptions, for instance, all the protocols described in Sub-Chapter 3.2 were subject to specific searches. The literature review lasted from January until the end of May i.e. the whole writing period of the thesis and there were not used any specific inclusion or exclusion criteria. This non-restrictive literature review approach was used for its convenience. It would have been very time-consuming to conduct this literature review according to a systematic review approach, as for instance David Goughs nine-phase process as described in Gough (2007), and give relatively low data quality increase in return.

The material obtained from the literature review were mostly secondary data. Secondary data are: "Data that have been collected by others for another purpose than the purpose of the current study. Some secondary sources are statistical bulletins, government publications, published or unpublished information available from either within or outside the organization, company websites and the Internet. The nature and the value of secondary data should be carefully evaluated before it is used" (Sekaran and Bougie, 2016, p. 37). Figure 2.3 on the next page shows the main categories of the secondary data. As can be seen from the figure, the data can be divided into four categories: Standards, public sources, peer-reviewed sources and market reports. The figure shows that the International Organization for Standardization (ISO)-standard 16484, which basically describes the BACnet protocol, was used. The public sources were newspaper articles and content on official websites. The material found on such secondary sources was important when writing about the specific protocols and about the case enterprise. Such sources were also essential in finding information regarding important protocol measures. The peer-reviewed sources were mainly articles gathered from the databases Emerald Insight, Science Direct, ProQuest and IEEE Xplore (discovered in the Oria and Google Scholar searches). There were also used several theoretical books. Market reports were an important part of this research, even though it was not possible to get access to reports assessing the main theme of the RQ.

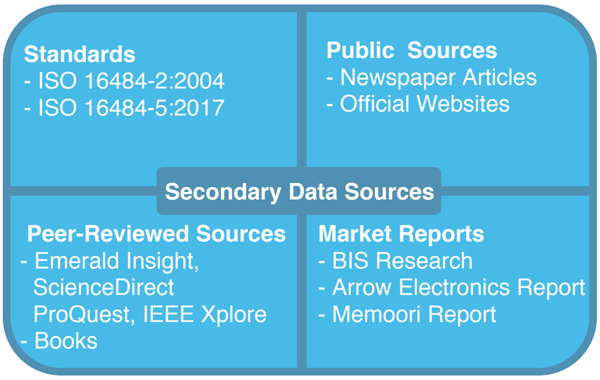

Figure 2.3: Overview of the secondary data sources

In a research of this kind, it is beneficial to also include primary data. Since primary data is the nearest one can get to the truth, misinterpretations are uncommon. Using such data will therefore increase the quality of the research. In the next sub-chapter the primary data collection method, interview, will be described.

2.2.2 Interviews

Using the interview method for data collection was chosen because of several combined reasons. Firstly, large parts of this research use the qualitative method. Qualitative research is according to Creswell (2014), an approach to exploring and understanding the meaning individuals or groups ascribe to a social or human problem. Interviews are a suitable method to find the meaning of individuals. Secondly, the information gained from the interviews were impossible to obtain from other sources, since the data obtained from the interviews were either confidential for the general public or not written down at all. Thirdly, interview data are primary data, and have thus a high reliability, and is accordingly a desirable data collection method on a general basis.

A semi-structured interview is an interview between two or more persons where the interviewer has prepared an interview guide. The interview guide is a set of questions and topics that need to be covered during the conversation, usually in a particular order. What makes the interviews "semi-structured" is that the interviewer is able to follow topical trajectories in the conversation that may stray from the guide when he or she feels this is appropriate. (Cohen and Crabtree, 2006)

This kind of interviews have according to Cohen and Crabtree (2006) two distinct benefits: Firstly, that many researchers like to be prepared and appear competent during the interview and secondly, to allow informants and the interviewer to express their views in their own terms according to where the conversation flows. Cohen and Crabtree (2006) further describe that the semi-structured interview guide provides a clear set of instructions for interviewers and can provide reliable, comparable qualitative data and that the opportunity to follow relevant topics that may stray from the interview guide provides the opportunity to identify new ways of seeing and understanding the topic.

During the project period, one semi-structured interview and several conversations with the Laboratory Manager at Glamox were conducted. The interview and conversations lasted between 30 and 60 minutes and all of them was performed during the writing period. The semi-structured interview was recorded while the conversations were not. The bullet point below shows the main characteristics of the semi-structured interview.

- 30.01.18 - Telephone interview with Sales Director LMS, PBS division Glamox AS. The System Responsible LMS, PBS division Glamox AS, also participated in the interview. The interview lasted approximately one hour (53 minutes) and evolved around protocols and trends in LMSs. The interview was recorded and fully transcribed afterwards.

As can be seen from the bullet point over, the interview was performed with two interviewees. This is the smallest form of group interview. Group interviews/focus groups have some inherent limitations since strong individuals might bias the results and the participants may be inhibited or “in role” (Cameron and Price, 2009). These factors did however not seem to dominate this interview, and Sub-Chapter 2.4 discusses such aspects more in detail.

The Laboratory Manager at Glamox AS Molde, which is also one of the supervisors of this thesis, was not formally interviewed but participated in several open-ended conversations. These conversations gave the researcher insights about technical features in the emerging trends in the lighting industry and other interesting viewpoints on for instance the development of standards, supplier demands, customer focus etc.

The semi-structured interview were fully transcribed but only the most relevant information from the interview was used in the thesis. The general impression regarding the interviewee’s view and opinion on the current status of Glamox and the lighting and building industry in general was the most important takeaway from the interview and conversations. Throughout this report, information gained directly from the semi-structured interview or conversations will be cited in the following way: (Interview/Conversation, Person/Title, 2018). In the process of writing the project thesis (pre-work for this thesis), two semi-structured interviews were conducted. These interviews have contributed with relevant material to this thesis as well and this material will be cited as: (Project Thesis, Interview, Person/Title, 2017).

2.2.3 Questionnaire

“Questionnaires are a means of asking a large number of people about what they think, feel or do. A questionnaire is a standard set of predetermined questions presented to people in the same order. It is normally self-administered but can also be used over the phone or face to face, although that is normally more costly” (Cameron and Price, 2009, p. 334).

One questionnaire was performed during this thesis’ writing period. The questionnaire was titled “Questionnaire: Communication Protocols in Building Management Systems (BMSs)” and can be found in Appendix B. This appendix also explains the researcher’s general impression regarding the questionnaire study. The questionnaire was conducted by approaching relevant individuals and politely informing them about this thesis and the purpose of the questionnaire. If he/she agreed to participate he/she was given a hard copied sheet of the questionnaire, a pen and time and support to fill out the sheet. A total of 48 responses were obtained from people in the building or light management industry. From March 20th to March 23rd the researcher was attending the Light + Building trade fair in Frankfurt. This is the world's leading trade fair for lighting and building services technology presenting intelligent and networked solutions, future-oriented technologies and current design trends (Light+Building, 2018). Most of the questionnaire responses were obtained from people representing their organization at stands on this trade fair (43 of the responses).

The questionnaire method for primary data collection was chosen because of its obvious advantages. According to Cameron and Price (2009), a questionnaire can be distributed with low expense to a large number of people and give different pieces of information which cumulatively contribute to your inquiry, or help to refine the next stage of data-gathering. Cameron and Price (2009) further stated that "Questionnaires are particularly useful when: your resources are limited; you want to collect data from a lot of people; these people can be accessed and are likely to be able and willing to respond to the questionnaire you send them; you know the questions you want to ask; you are sure that they are easily understood" (Cameron and Price, 2009, p. 337). All these factors came evident in this research.

The RQ of this report is of such kind that a final answer was impossible to find in published literature or similar. The primary data obtained from the questionnaire was therefore essential in answering the RQ. Cameron and Price (2009) emphasized that questionnaires must be based on a clear and specific research question/purpose and that one must know precisely what information is required to answer that research question to gather proper data.

A useful questionnaire is carefully and skillfully designed with a focus on the two key elements; content and design. The content of the questionnaire is the questions and one usually distinguishes between two main types of questionnaire questions, namely open and closed questions. To achieve balance, many questionnaires tend to use a mixture of the two. Open questions ask respondents for perceptions, views or explanations and have to be clearly expressed so the respondents can identify the key themes and develop their own answers. Adding open adjuncts or open "Other" categories helps to elicit explanations or gather a wider set of responses that are more reflective of the views of the respondents. Closed questions, also known as forced choice questions, present the question and a limited range of responses from which to choose. Closed questions are useful for obtaining comparative or statistical data, or for getting people to rank their preferences, and can be presented in a number of ways like yes/no questions, category choice questions, Likert scales, differential scales and rank orders. (Cameron and Price, 2009)

The questionnaire of this thesis is heavily based on closed questions, with one question having an open "Other" category and one totally open question. The closed question usage was chosen because of the nature of the RQ and because the researcher wanted to gain quantitative, comparable data. The closed questions were category choice questions and Likert scales questions. Category choice questions give the respondents a given set of available answers in which to choose from and should according to Cameron and Price (2009), not contain more than seven categories which are comprehensive, of equal size, and mutually exclusive. Likert scales are named after the psychologist Rensis Likert who first used the scales in the 1930s to describe attitudes. Likert scales are constructed in an agree/disagree order and should have an odd number of response categories to allow for a neutral reply. These questions should also be used intermittently to prevent central tendency bias from distorting the data. As can be seen from the questionnaire in Appendix B, the questions are of the following type and order: Category, Likert, Likert, category and totally open. This was an intentional choice to avoid a central tendency bias in which the respondents thick the middle box without thinking about their responses. The researcher thinks that the two Likert questions in a row will not lead to any bias.

Cameron and Price (2009) stated that a well-designed and well-structured questionnaire engages the respondents and encourages them to answer the questions honestly and accurately. To do this the questionnaire must be visually appealing, not too long and only ask those questions specifically relevant to the inquiry and ask them in the most concise way possible. The most likely respondents of the questionnaire of this thesis are in some kind of manager position. These respondents do according to Cameron and Price (2009) often prefer a professional design with minimal or no use of colour and image and has been taken to account in the construction of the questionnaire. However, the questionnaire includes one figure which is seen to be an essential part of question 2. The figure was implemented to reduce the chance of misinterpretations and to get a common reference for all respondents and was made as straightforward as possible.

Question 2 on the questionnaire asks the respondents to tick one protocol for each BMS level. This seemed to be overlooked or misinterpreted by many of the respondents since 23 of them ticked more than one protocol for one or several of the BMS levels. These questionnaire sheets were logged separately and compared with the questionnaire sheets that had ticked only one protocol per BMS level. The results were found to be similar to a large degree and it was therefore decided to use the questionnaire sheets with more than one thick per protocol on question 2 as equal evidence as the "correct" questionnaire sheets. It also has to be stated that the researcher tried to get the respondents to only tick one protocol when it was noticed that more than one protocol was ticked. Some of the respondents changed their answer accordingly and others said that it was too hard to only choose one protocol. This reflects the struggle many industry actors have to deal with in the choice of communication protocol.

There is one partly sensitive (or personal) question on the questionnaire, question 3, which asks about the current working title. This question has been put in the end because the respondents might be more relaxed and having completed the questionnaire they know the type of data their personal details could be connected to (Cameron and Price, 2009). This last question got fewer answers than the rest of the questions because the respondents seemed to overlook it. This might be because the question did not have any categories to tick and/or because it was in the end. This question should, therefore, have been constructed in another way to get as many answers as the rest of the questions. There is also important to assess confidentiality issues when constructing a questionnaire, which has been done in the introduction (covering letter). By stating that: "... your responses will be treated in confidence and will be used only as part of this research project. Your anonymity will be respected and there will be nothing in the results that might connect you or enable others to connect you to the data" the confidentiality issue is certainly taken care of. The introduction also holds general information regarding the objective of the questionnaire, how long it will take to complete it, how many pages it has and contact details. This is according to Cameron and Price (2009) important information to include. Since most of the questionnaire responses were gained while the researcher was present, this information was after the execution of the questionnaire seen as a bit superfluous.

To sum up, the questionnaire of this thesis was seen to be a success and an essential contribution to the analysis of this thesis. The researcher thinks that the main reason for the success is the shortness of the questionnaire. Most people got a few minutes to spare a research student at a trade fair. There is also important to state that the questionnaire method for data collection holds several limitations, most of them connected to misinterpretations of the questions. With the researcher present during the time the respondents used to fill out the sheet, such limitations are minimized. The results of the questionnaire will be presented and interpreted in Chapter 5. In the next sub-chapter, the data analysis methods will be discussed.

2.3 Data Analysis Methods

In order to analyze the data found in the questionnaire and to assess the strategic environment for Glamox AS, four data analysis methods were used. Porter's five force analysis, graphical analysis, non-monetary CBA and MCA. The underlying methodology of these analyses will be described in this sub-chapter.

2.3.1 Porter's Five Forces Analysis

"The Five Competitive Forces That Shape Strategy" is a strategic tool for organizations and enterprises. It was first introduced by Michael Porter in 1979 and have since then shaped a generation of academic research and business practice (Porter, 2008). It is a tool for investigating the competitive environment and can be used for both a current status assessment and in a pre-development or development phase. According to Porter (2008), strategy can be viewed as building defences against the competitive forces or as finding a position in an industry where the forces are weaker. Porter (2008) further stated that changes in the strength of the forces signal changes in the competitive landscape critical to ongoing strategy formulation. The following sections present the characteristics of the five forces as described in Porter (2008):

Threat of New Entrants. New entrants to an industry bring new capacity and a desire to gain market share that puts pressure on prices, costs, and the rate of investment necessary to compete. Particularly when new entrants are diversifying from other markets, they can leverage existing capabilities and cash flows to shake up the competition. The threat of entry in an industry depends on the height of entry barriers that are present and on the reaction entrants can expect from incumbents. If entry barriers are low and newcomers expect little retaliation from the entrenched competitors, the threat of entry is high and industry profitability is moderated. It is the threat of entry, not whether entry actually occurs, that holds down profitability.

Bargaining Power of Suppliers. Powerful suppliers capture more of the value for themselves by charging higher prices, limiting quality or services, or shifting costs to industry participants. A supplier group is powerful if: It is more concentrated than the industry it sells to, the supplier group does not depend heavily on the industry for revenues, industry participants face switching costs in changing suppliers, suppliers offer differentiated products, there is no substitute supplier and if the supplier group can credibly threaten to integrate forward into the industry.

Bargaining Power of Buyers. Powerful customers – the flip side of powerful suppliers – can capture more value by forcing down prices, demanding better quality or more service (thereby driving up costs), and generally playing industry participants off against one another, all at the expense of industry profitability.

Threat of Substitute Products or Services. A substitute performs the same or a similar function as an industry's product by a different means. Videoconferencing is a substitute for travel. Plastic is a substitute for aluminum. Email is a substitute for express mail. Substitutes are always present, but they are easy to overlook because they may appear to be very different from the industry's product. When the threat of substitutes is high, industry profitability suffers. Substitute products or services limit an industry's profit potential by placing a ceiling on prices. If an industry does not distance itself from substitutes through product performance, marketing, or other means, it will suffer in terms of profitability – and often growth potential. Substitutes not only limit profits in normal times, they also reduce the bonanza an industry can reap in good times. In emerging economies, for example, the surge in demand for wired telephone lines has been capped as many consumers opt to make a mobile telephone their first and only phone line.

Rivalry Among Existing Competitors. Rivalry among existing competitors takes many familiar forms, including price discounting, new product introductions, advertising campaigns, and service improvements. High rivalry limits the profitability of an industry. The degree to which rivalry drives down an industry's profit potential depends, first, on the intensity with which companies compete and, second, on the basis on which they compete. The intensity depends on the number- and size of the competitors, industry growth, exit barriers and commitment of rivals. The basis on which they compete can range from price, product features, support services, delivery time or brand image. The price competition has the largest potential to erode profitability.

Porter (2008) emphasizes that understanding the forces is the starting point for developing strategy. He further stated that every company should already know what the average profitability of its industry is and how that has been changing over time. The five forces reveal why industry profitability is what it is and the most significant aspects of the competitive environment. They also provide a baseline for sizing.

The five forces of Porter were in this report used to analyze the competitive landscape of the LMS segment of Glamox AS. Finding the content and strength of the five forces was based on the knowledge about the trends and future prospects regarding smart buildings and the use of communication protocols (Chapter 3) and the current LMS and general status in Glamox. In the construction of the forces for Glamox, several aspects from the theory about the forces came evident: The most important from the *Threat of New Entrants*-force were found to be that enterprises that are diversifying from other markets can shake up competition. For the *Bargaining Power of Suppliers*-force, all the aspects of a powerful supplier were found relevant. The *Bargaining Power of Buyers*-force emphasized the importance of providing quality products that satisfy customer demands. The *Threat of Substitute Products or Services*-force emphasized the importance of distancing itself from substitutes through product performance, marketing, or other means. *The Rivalry Among Existing Competitors*-force shed light on new product introductions and service improvements.

The IoT leads to disruptive changes and the lighting industry is no exception. Digital technologies equal new possibilities. Partnerships, strategic cooperations and outsourcing have the potential to redefine the borders of an industry. When evaluating the five forces for Glamox, it was necessary to expand the scope from the traditional lighting industry to include actors from other industries as well. This means that the traditional scope, lighting, was transformed to include the whole "smart building" and actors from totally different industry segments had to be evaluated as possible entrants. Even though the five forces model were constructed by Porter to evaluate the competitive landscape for a specific defined industry, his model was found to be highly relevant for the evaluation of the redefined industry scope in this context as well. This reflects the agility of the tool.

2.3.2 Graphical Analysis of Questionnaire

The questionnaire result was logged and analyzed in Microsoft Excel. Two types of graphical representation of the data were used: Pie and bar charts. Displaying data graphically can according to Cameron and Price (2009) provide a lot of information but will also increase the "perceived value". In the two following sections, pie and bar charts will be described.

Pie charts are formed like a pie (a circle) where the whole pie represents the sample. Appendix C displays several pie charts. The pie is divided into slices, each slice showing the proportion of a category. A pie chart gives a good impression of relative proportions, provided that there are not too many slices. More than six slices can be difficult to read and very thin slices are also difficult to read. Despite these limitations, pie charts are popular because of their attractive appearance and visual impact and can improve the presentation of the data if used on a suitable sample. (Cameron and Price, 2009)

Bar charts are composed of bars representing a percentage or a frequency of a given category of a sample. The full sample is represented by the sum of all the bars. Appendix C displays several bar charts. The bar charts used in this thesis has separate bars with a distance between the bars. This is good practice and makes it harder to assume (wrongly) that the categories are in any sense part of a "scale" (Cameron and Price, 2009). The main difference between the pie and bar charts used in this thesis is that the pie charts expresses the results in percentage values while the bar charts represent them as the actual number of ticks in the given category.

These two chart types were chosen to display the results of the questionnaire because they are familiar for the most likely readers of this thesis and because they are visually appealing. The two types of charts also display much information in little space. Especially the bar charts were found to be very space effective, displaying the whole result of each of the questionnaire questions in one diagram each.

2.3.3 Non-Monetary Cost-Benefit Analysis

According to Boardman et al. (2011) a Cost-Benefit Analysis (CBA) is a policy assessment method that quantifies in monetary terms the value of all consequences of a policy to all members of society. They further stated that CBA applies to policies, programs, projects, regulations, demonstrations, and other government interventions. In this master's thesis, CBA has been used to compare the costs and the benefits of two communication protocol solutions at the field level (the field level will be described in Chapter 3). Because of the limited time span and the information available, cost and benefit estimates in monetary values were impossible to find with even a large uncertainty span. Because of this, the CBA of this thesis do not use monetary values and will not present estimates of actual costs and revenues in the two protocol solutions. Instead, a ranking scale was used. Using such scales is often done in CBA's for the so-called non-monetary consequences/effects/costs/benefits ("ikke-prissatte konsekvenser") (Boardman et al., 2011) (Direktoratet for økonomistyring, 2014). A scale from 0 to 10 was used and the difference between the two protocols was the main focus when setting the costs and benefits. This means that the magnitude was not the major concern, even though there were used some time in setting a likely magnitude of a post compared to the other posts. The CBA of this thesis takes place in Sub-Chapter 5.3 and the full analysis with an explanation of all the values can be found in Appendix H. As can be seen, the analysis is divided into costs and benefits with direct and indirect categories. When subtracting the total costs from the total benefits we get the "bottom line", the result. The CBA of this thesis is computed for four different stakeholders: Glamox, the building responsible (BR), the user and the general society.

According to Boardman et al. (2011), there are two major types of CBA's. Ex ante and ex post CBA. Ex ante CBA is conducted while a project is under consideration before it is started or implemented and assists the decision of whether a project is worth executing or not. Ex post CBA is conducted at the end of a project. At this time, all of the costs are "sunk" in the sense that they have already been used up to do the project (Boardman et al., 2011). The analysis of this thesis is ex ante and has the aim to be a part of the final decision making of which protocol is best suited.

There is little doubt about the fact that performing a CBA without monetary values gives less information than a CBA that does so. This is the main limitation of the CBA performed in this thesis. But using the same ranking scale for all the effects in the analysis makes it possible to get comparable answers. In the regular CBA's using monetary values, there will often be some effects that can not be expressed in monetary values. When such is the case the analysis must compare money with some effect scale which will limit the comprehensiveness of the final answer. A common way to measure such non-monetary effects is the "plus-minus" method, using a nine-wise scale ranging from outstanding negative consequence to outstanding positive consequence (Direktoratet for økonomistyring, 2014). There could be claimed that the CBA performed in this thesis is more similar to a Cost-Effectiveness Analysis or a Multigoal Analysis, as described in Boardman et al. (2011). This thesis will not go further into details regarding this since it was not the specific definition of the analysis that was of focus when performing this analysis. The aim was always the information and knowledge gained on the way and the interpretation of the results. Comparing the bottom line for the two solutions and between the different stakeholder categories was also of great interest.

Other limitations of this CBA, in addition to the non-monetary limitation, are: The choice of cost and benefit posts (could have included other posts or made another distinction between the posts), the environmental costs are influenced by the researcher's competence and view on this issue (will vary due to personal preferences and competence of the person conducting the CBA) and lastly, setting a ranking of the costs and benefits of the building responsible, the user and the society was a difficult task and must be read with caution.

2.3.4 Multi-Criteria Analysis

A Multi-Criteria Analysis (MCA) is as the name implies - an analysis that looks at multi (means more than one or many (Oxford Dictionary of English, 2018)) criteria. There exist a range of different MCA methods with diverse procedures for comparing and allocating scores to the criteria and alternatives. According to Cristobal (2012) multi-criteria decision-making methods is a branch of a general class of operations research models that is suitable for addressing complex problems featuring high uncertainty, conflicting objectives, different forms of data and information, multi interests and perspectives, and the accounting for complex and evolving biophysical and socio-economic systems. Cristobal (2012) further stated that there are four starting reasons that justify the use of MCA decision-making methods, namely, (1) MCA allows for investigation and integration of the interests and objectives of multiple actors; (2) MCA is a user friendly method with information that is comparable and easy to communicate to actors; (3) MCA is a well-known and applied method of alternatives' assessment that is formed to fit a specific problem and/or context; (4) MCA allows for objectivity and inclusiveness of different perceptions of actors without being energy and cost intensive.

The starting points of Cristobal (2012) presented above was seen to apply for the themes at question in this thesis as well, and there was seen to be applicable to construct an MCA assessing some of the main issues that came evident throughout this research. According to Cristobal (2012) the decision-making process usually includes five main stages: defining the problem, generating alternatives and establishing criteria, criteria selection, criteria weighting, evaluation, selecting the appropriate multi-criteria method and finally, ranking the alternatives. In the MCA performed in this thesis, three alternatives (Scenario 1, 2 and 3) was evaluated according to nine criteria (success factors). The stages of Cristobal (2012) was followed but the criteria were not given weights, only a score for each alternative. There was used a threefold scoring scale, 1 = Weak, 3 = Medium and 9 = Strong. The scenarios and the success factors will be extensively described in Chapter 5.

The main limitation of the MCA conducted in this thesis is the lack of supporting evidence for the quantification of the scores. The scores are of course based on the theoretical evidence, the case information and the various analyzes made throughout this thesis, but lacks some real statistical data foundation. This should be brought to mind when reading the MCA.

2.4 Quality of Data and Methods

An important part of the data extraction process is to assess the quality of the data. This is, according to Cameron and Price (2009), especially important for secondary data where the authors' selection and reporting are reliant on their diligence and judgment. The data may also come from a perspective that is slightly different from the perspective of the research. Assessing the quality of the primary data is of course also important, as well as assessing the quality of the different methods used to collect and analyze the data. In the following sub-chapters, the primary and secondary data and the data collection methods will be evaluated according to their relevance, validity, reliability, representativeness and generalizability. The quality of the data analysis will be discussed in the last sub-chapter.

2.4.1 Relevance

Relevance can be defined as the extent to which the data helps to answer your research question (Cameron and Price, 2009). Finding if the literature were relevant or not, were a large part of the general literature review and the procedure illustrated in the flowchart in Appendix A was used to assess the relevance of the material used in this thesis. One important aspect when it comes to assessing relevance is that this type of research is not static. The way ahead was formed as the research developed and some of the literature that was "archived" early in the research phase were found to be highly relevant towards the end.

The relevance of the primary material was generally easy to assess. The semi-structured interview and conversations discussed several themes and aspects that are beyond the scope of this report and such material were not used. The questionnaire was constructed with questions specifically targeted towards the RQ of this thesis and required pre-knowledge regarding building and light management communication protocols. This made the questionnaire itself and the responses to the questionnaire highly relevant evidence material in this thesis.

2.4.2 Validity

A measure is valid if it measures what it purports to measure (Cameron and Price, 2009). In this thesis, the secondary material was validity checked by comparing the work by different authors and nationalities and trying to find several independent works stating the same. There were also used some time in investigating whom the authors of the research articles were and the credibility of the organizational sources of information.

According to Cameron and Price (2009) face-to-face interviews are seen to have high validity since such interviews have apparent transparency (the same accounts for the general conversations). The interview was also audio recorded and fully transcribed shortly after the interview was finished. The questionnaire is seen to have high validity as well. The two supervisors of this thesis were given the questionnaire before the trade fair, providing comments and some last adjustments to limit any possible confusion. The fact that the researcher was available for all the respondents when they responded to the questionnaire, gave the respondents the possibility to ask questions. Because of this, the questionnaire is seen to have measured what it was purposed to measure, and thus to be valid.

2.4.3 Reliability

Reliability is according to Cameron and Price (2009) the statistical likelihood that repeating the data-collection exercise will produce similar, if not identical, results. The main drawback of the general literature review is the subjective interpretation of the reliability of the data. If this exact research were performed by another researcher, there would certainly be other articles/books in the bibliography and the material would have been interpreted differently. Since this research has been performed by only one researcher the interpretation argument is even stronger.

According to Cameron and Price (2009), the limitations of secondary-data-only research relate fundamentally to the theme of reliability. They state that issues of finding out how timely the information is, how reliable the sources of information are, what has been done to the data to change it into information, and whether or not the data from different sources are comparable, must be taken into account. The reports by Silvair (2018) and Memoori (2017) stand out as important contributions to Chapter 3 of this report. These two reports are written by organizations and are not scientific work by definition. Because of this, the reports might be biased by the underlying norms of the organization, and this is a limitation of using such material. When assessing the quality of the material it is always important to have in mind that the author's opinion might be an underlying factor for the written material, even in scientific articles. In an attempt to limit this bias, the researcher has tried to find several articles stating the same, independent of each other's work (as stated in the validity assessment), and to have an objective point of view on the evidence.

The reliability of the interview should also be assessed. According to Cameron and Price (2009), semi-structured interviews have some reliability. The interviewees had a friendly tone towards each other and the researcher, seemed to be comfortable in the interview setting and to answer the questions truly. The questionnaire is also seen to be reliable. The reason for this is that all the respondents were given the same questionnaire sheet and all of them had the possibility to ask questions to the researcher while answering the questionnaire. With a sample of 48 respondents, there can also be claimed to have enough responses to assume a normal distribution (due to the central limit theorem, see for instance LaMorte (2016)) and therefore also a reliable result since repeating the data-collection exercise will be likely to produce similar results.

2.4.4 Representative

According to Cameron and Price (2009), data is representative if it is typical for some larger group about which you wish to learn. Assessing the representativeness of the literature used in this thesis was not of any major concern during the writing process. This is because the nature of the theoretical evidence in this research is widely differing. Even though there were used a great deal of time to find solid sources of evidence, many of the articles used in this thesis discuss specific aspects of the technological themes and may thus not be representative for the whole “group”.

Representativeness was, however, of focus when writing about the more general themes as smart buildings and trends in building management. Using broad reports from well-known organizations and some theoretical books contributed to the representativeness of these sub-chapters. The sources used in the methodology chapter are also solid, general, sources. The primary data from the semi-structured interview and conversations with Glamox employees have a low representativeness since only a few persons were questioned and because the persons were asked different kinds of questions depending on their competence. The questionnaire is seen to be representative because of the relatively high number of respondents and because of the homogeneity of the answers. Nevertheless, with the misinterpretations of question 2 (as discussed in Sub-Chapter 2.2.3) and the inclusion of these answers, the questionnaire result can be claimed to be less representative.

2.4.5 Generalizability

Closed connected to representativeness is generalizability. Cameron and Price (2009) described generalizability as the extent to which generalization is justified and further stated that generalization is a process of making claims about a wider category based upon findings from a single case or a smaller set of findings or sub-category. The case study approach of this thesis makes a generalizability assessment relevant. Can the use of Glamox as case enterprise be transferred to account for another enterprise in the BMS environment or for the whole BMS system case? Since the main scope of this thesis is communication protocols in professional buildings, the degree of generalizability will vary among the different levels of building management (these levels will be extensively described in Sub-Chapter 3.1.3). Transferring to another lighting enterprise, would not induce any overwhelming change of this research’s results since the field level devices are the same. However, transferring to another technical building actor, as for instance taking the perspective of the Norwegian based Heating, Ventilation and Air Conditioning (HVAC) enterprise GK would lead to a totally different field level analysis.

Transferring to looking at the whole BMS would also lead to another angle of the research. The field level would then have to be expanded to include all the different technical systems in a building. The analysis done of the automation and management level (based on Glamox) is found to be highly generalizable as these levels include all the other technological systems as well.

2.4.6 Quality of the Data Analysis

The data analysis of this thesis takes place in Chapter 4 and 5. Porter’s five forces analysis (described in Sub-Chapter 2.3.1) and a brief stakeholder analysis were used to analyzing the current competitive situation for Glamox. The case analysis is seen to be relevant, valid and reliable. This is because the analysis is directly connected to one of the SQs of this thesis and because there were found sufficient information to make a suited assessment. Assessing representativeness and generalizability of this analysis is not relevant.

The analysis chapter of this thesis, Chapter 5, is composed of the questionnaire analysis, the CBA and the MCA. Using three methods that complement one another results in a triangulation in analysis methodology and significantly increases the quality of this research. The three methods sheds light on their own aspect of the subject, makes the analysis more solid and limits the possibility of drawing the wrong conclusions.

In this chapter, the whole methodology stack of this thesis has been presented and explained thoroughly. The next chapter, Chapter 3, is the theory chapter. Here, the evidence drawn from the literature review will be expressed.

Chapter 3

Theory

There are several steps that need to be executed in answering the RQ of this thesis. In this chapter, the theoretical foundation will be presented. Important concepts and terms will be explained in such a way that the evaluation of the different possibilities and solutions regarding communication protocols in the future LMSs and BMSs will be understandable for the reader. Depending on the importance of the terms and concepts, some will be thoroughly explained and others only vaguely. This chapter starts by explaining the development of professional buildings and BMSs. After this, communication protocols, the Open Systems Interconnection (OSI) model, important technological devices and important protocol measures will be explained. The last sub-chapter, Sub-Chapter 3.3, introduces and compares the most frequently used communication protocols in buildings.

3.1 Building Management Terms

Due to, among other things, increased focus on environmentally friendly solutions, technology advancements and stricter restrictions from governments, buildings has changed a lot during the past decades. This sub-chapter aims at answering SQ (a), "Which trends are emerging in the building and BMS landscape?" The two first sub-chapters describes the development from intelligent to smart to thinking in general, in buildings and in BMSs. The last sub-chapter explains and illustrates the current BMS architecture and introduces the three levels of BMSs.

3.1.1 Intelligent → Smart → Thinking

Labelling things, systems and various technologies as "Smart" is not unusual today. But what does it really mean to be a "Smart Something"? IGI Global, an international academic publisher organization, have found the following definition of smart technologies: "The technologies (includes physical and logical applications in all formats) that are capable to adapt automatically and modify behavior to fit environment, senses things with technology sensors, this providing data to analyze and infer from, drawing conclusions from rules. It also is capable of learning that is using experience to improve performance, anticipating, thinking and reasoning about what to do next, with the ability to self-generate and self-sustain" (IGI Global, 2017).

In private homes, smart technologies have begun to gain footing. At present, it is mostly individuals with an over average technological competence and/or interest that lives in smart homes but as the costs of such systems decrease and the consumers get more aware of the possibilities associated with such systems, it is expected to be a steady increase of the number of smart homes in the next years. This has been confirmed by many industry actors and various market reports, as for instance the research done by Markets and Markets, who found that the global smart home market is predicted to grow almost 14 % per year between 2017 and 2023 (Liu, 2017). Homes have gotten smart faster than professional buildings and there are of course obvious reasons for this, such as costs and quality demands. In homes, there is maybe enough to change ten light bulbs, insert some sensors and change the door lock - and you are good to go. With buildings, the size is at a totally different scale, and so are the costs. There are also usually much more strict quality and security restrictions.

It is not difficult to see that the IoT has made it possible to make things smart and that there are certain similarities between the IoT and "smart things". An important remark in this regard is that having something on the Internet is not a prerequisite in making something smart. What is essential in the "smartness" context is to utilize technology and make algorithms i.e. rules so that the "thing" can act smart. Other terms we see popping up are "intelligent technology/things" and "thinking technology/things". There are different interpretations of these terms as well, but the general opinion in the evaluated literature is the following evolution sequence with increasing "smartness": Intelligent to smart to thinking. This can again be transferred to a reactive to adaptive to predictive control flow (Buckman et al., 2014). Figure 3.1 on the next page puts all these terms into the building context and describes important characteristics among the three types of buildings. The content of the figure is copied from Buckman et al. (2014).

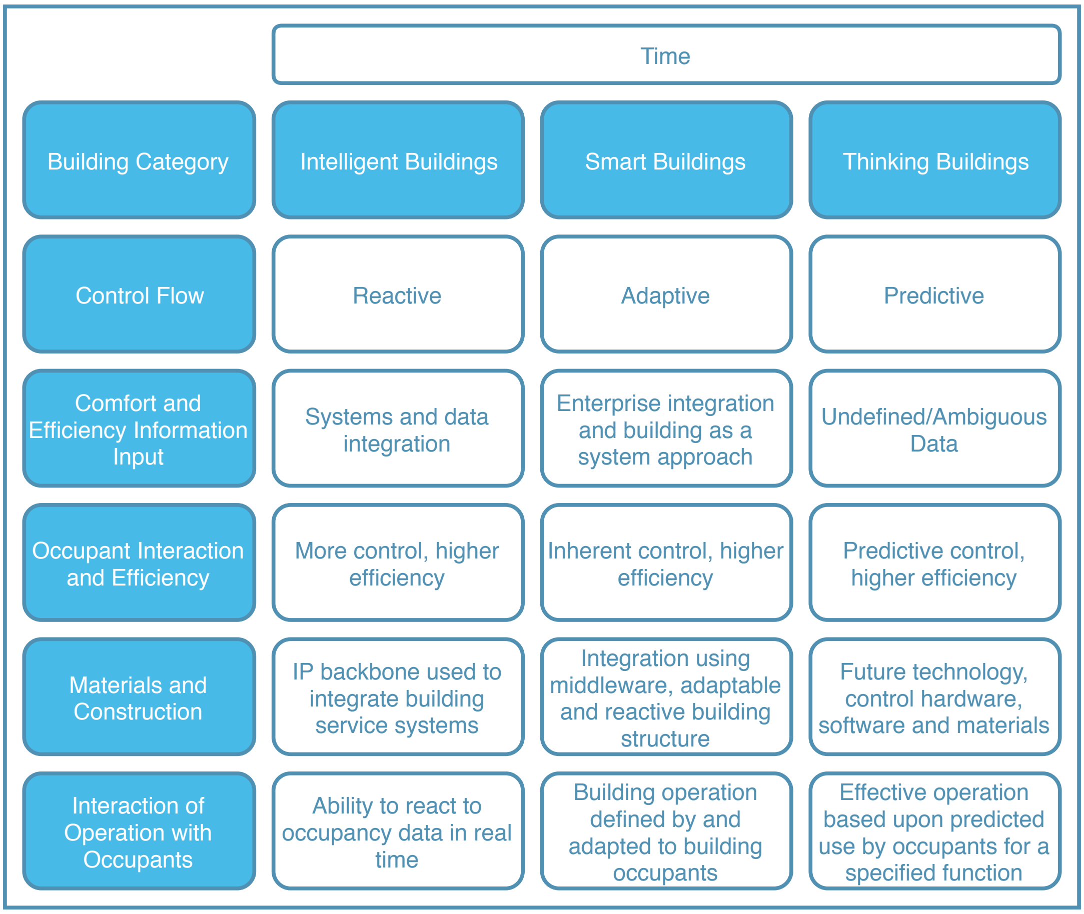

Figure 3.1: Intelligent, Smart and Thinking Buildings (Buckman et al., 2014, p. 95)

Looking at this figure and reflecting over the professional buildings currently existing, one can claim to have buildings at all these stages. There are however several reasons to allege that most buildings today are intelligent (or less than intelligent) - at least in Norway. As quoted by Ghaffarianhoseini et al. (2016), many different buildings have been labelled as intelligent over the past 20 years. However, the application of intelligence in buildings has yet to deliver its true potential (Ghaffarianhoseini et al., 2016). Even though we are along a path towards smart buildings, the path is far from at its end. With the introduction of the IoT and wireless connectivity, all the main features of smart and even thinking buildings are possible to include in already existing buildings. If the true potential of the IoT is utilized there is not unlikely that buildings can go directly from being less than intelligent to being thinking.

At the very heart of getting to thinking buildings is the BMSs. This is because these systems monitor, analyze and display the data needed to get buildings that can predict the future and take actions based on predefined scenarios. With more advanced sensors and prediction software getting thinking buildings is a possibility. The next sub-chapter will define what a BMS is and explain the history of such systems.

3.1.2 Building Management Systems

"All technology systems in a building are networks consisting of end devices that communicate with control devices or servers to monitor, manage, or provide services to the end devices. Communications between the devices occur via a set of rules or protocols. Connectivity between devices on the network is either through cable or a wireless transmitter/receiver. The network typically has a system administration workstation or PC that provides a management and reporting function" (Sinopoli, 2010, p. 7).

The sum of the networks described in the quote by Sinopoli (2010) over is the building's BMS which is going to be an important concept of this master's thesis. The system that manages the building's technical systems is known by many names which are often used interchangeably in academic literature, theoretical books and among the building industry actors. The most used terms are BMS, Building Automation Systems (BAS), Building Management and Control System (BMCS), Direct Digital Controls (DDCs) and Building Controls (BC) (Kastner et al., 2005) (Smith, 2018). Throughout this thesis, the term BMS will be used in the same way as Memoori (2017) does it, namely to describe the computer-based control system that monitors and manages a building's mechanical and electrical equipment, including ventilation, lighting, power, fire and security systems.

The historical roots of building automation are in the automatic control of HVAC systems, which have been subject to automation since the early 20th-century. "The oil price shock in the early 1970s triggered interest in the energy savings potential of automated systems, whereas only comfort criteria had been considered before. As a consequence, the term "energy management system" (EMS) appeared, which highlights automation functionality related to power-saving operation, like optimum start and stop control" (Kastner et al., 2005, p. 1179). As time went on there were discovered that other building service systems could benefit from automation as well. Recognizing the head start of the Building Automation (BA) systems of the HVAC domain with regard to control and presentation, they provided the natural base for successive integration of other systems (sometimes then termed "integrated BMS" (IBMS)). (Kastner et al., 2005)

Figure 3.2 on the next page is the "Intelligent building pyramid" and shows the development of the interplay between the different technological systems in a building from the 1980s up until present time. The figure illustrates the development from the technological silos to the more complete, merged, system where the different vertical silos are horizontally integrated. The quote from Memoori (2017) fits well with the development illustrated in the figure: "As BMS and the IoT continue to develop we will see greater cost savings and new features, creating unprecedented value from the building. The future of buildings is data rich and connected, and more than just embracing these characteristics, BMS has risen to become the blood stream and beating heart of the smart building" (Memoori, 2017).

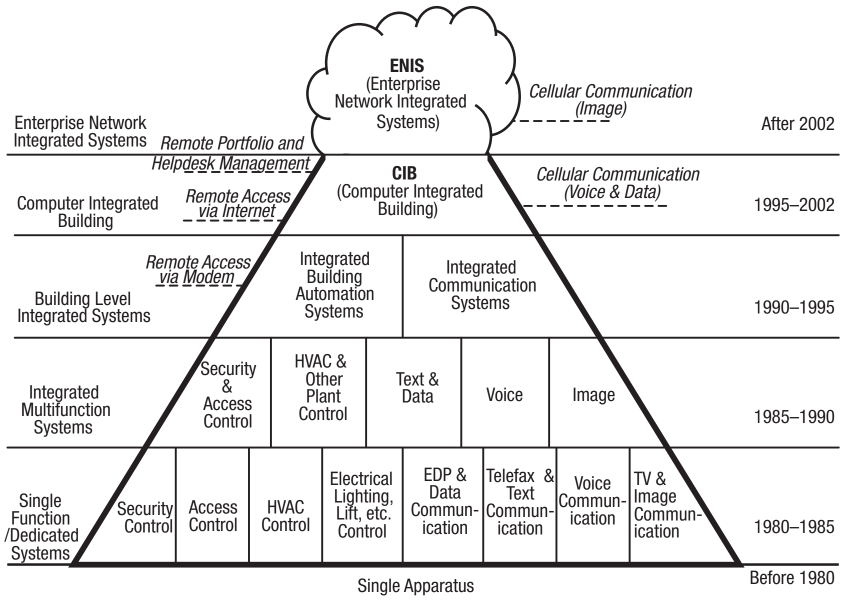

Figure 3.2: Intelligent Building Pyramid (Wang, 2010, p. 7)

Wang (2010) stated that along with the rapid evolution of electronic technology, computer technology and information technology, Intelligent Building (IB) systems are becoming more and more advanced, and the level of integration is being developed progressively from the subsystem level to total building integration and convergence of information systems. The open top of the pyramid emphasizes that the IB systems are not enclosed within buildings anymore but instead are merged with IB systems in other buildings as well as other information systems via the global Internet infrastructure (Wang, 2010). Figure 3.2 illustrates that BMSs has been boosted by the technological developments of the time and that today's smart building technology is influencing BMSs like nothing before (Memoori, 2017). According to Memoori (2017), the trends promoting growth in the BMS market can be directly linked to the IoT movement and it is seen to be a tendency towards lower cost of "things" with embedded intelligence, advances in predictive analytics, as well as a growth of cloud based services (Memoori, 2017).

According to the intelligent building pyramid, we are currently at the "Enterprise Network Integrated Systems"-stage - which seems like a really good and integrated stage to be in. The actual picture is however not as good as it looks. The article by Memoori (2017) stated that the traditional way of operation where each technical system has their own IT structure is changing to integrated solutions where the BMS, consisting of both hardware and software, is configured in a hierarchical manner. The problem with integrating the systems is that it is not performed in full scale. According to Bovet et al. (2014) we are currently observing the coexistence of different network technologies, often caused by the installation of new equipment answering specific physical constraints, for example, wiring and power supply. Bovet et al. (2014) further stated that the protocols are often relying on proprietary layers and that this heterogeneity actually leads to two situations. "In the first one, several BMS are coexisting and share the management of independent equipment, making difficult any global optimization. In the second one, a unique but more complex and costly BMS is used where bridges to the different protocols are integrated" (Bovet et al., 2014, p. 2). Based on this, Bovet et al. (2014) stated that we can reasonably converge to the fact that there is a lack of standardization in BAS systems at both the network and at the application layer of the OSI model (The OSI model will be explained in Sub-Chapter 3.2.1). The author of this master's thesis certainly agrees.

The next sub-chapter will present the architecture of most BMSs available today and it will come evident that these systems can have a quite complex architecture. As stated by Wang et al. (2011), the classical BMSs is divided into layers, each layer serving a particular set of functions and devices and employing specific network technologies suited to its inherent characteristics. Even in the same layer, heterogeneous network protocols coexist, not only depending on the building service domain but also political motivation of the integrator (Wang et al., 2011).

3.1.3 Current BMS architecture

A BMS consists of sensors and actuators, wires, digital controllers, software, command centres and so on. There is not one standard set of components or functions in a BMS, meaning that most buildings have their own unique solution. This is because there exists a bunch of different systems that can be used and it becomes a choice of preference of the given system operator. It is usual to divide the system into three levels (or layers), namely the field, automation and management level. Figure 3.3 below illustrates the three levels and shows a typical BMS architecture in present buildings. The three levels are often found as various segments of the physical building (room, floor etc.) but there is no clear definition of this. The most used communication protocols at the different levels are also shown in the figure. Communication protocols will be described thoroughly in Sub-Chapter 3.2.

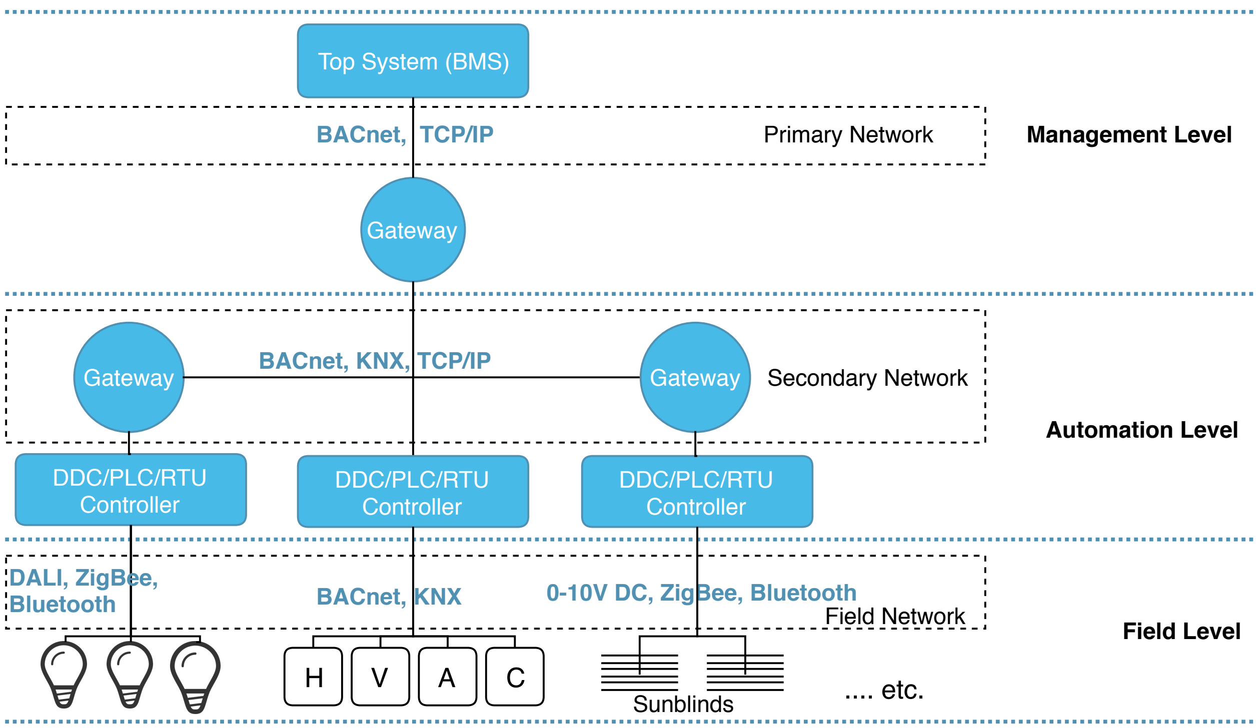

Figure 3.3: Typical BMS architecture today

At the bottom of the figure, we find the field level. This level consists of the sensors and actuators providing measurements and actuation (Bovet et al., 2014). This level has a dedicated bus communication system, named fieldbus, which interlinks the sensors and actuators (Wang et al., 2011). The network protocols operating at this level focus on reliability, maintainability, determinability and the convenience (Wang et al., 2011). A field network is according to ISO (2004) a communications connection between actuators/sensors and room devices with control devices. Even though it is the network that operates the fieldbus, the terms fieldbus and field network is often used interchangeably. Figure 3.3 has a box, "DDC/PLC/RTU Controller" after the field network. These components are normally the masters in the field domain and collect data from sensors, execute logic or sequence calculation, and send computation result data to the actuators (DDC = Direct Digital Controller, PLC = Programmable Logic Unit, RTU = Remote Terminal Unit) (Wang et al., 2011). There exist several general-purpose fieldbus systems such as LonWorks, KNX and BACnet. However, these protocols are implemented in little degree compared to the more purpose made protocols (as DALI for lighting). This is according to Wang et al. (2011) because building services such as the lighting system, security system, fire alarming system etc. are so abundant in content and none unique technology suits all domains of buildings. Another important aspect to comment when speaking about the field level is the IoT. The general view of the IoT is about connecting everything to the Internet and doing this in buildings means connecting the field level devices to the Internet.

The next level is the automation level, which provides control logic for driving actuators, providing some kind of intelligence to the building (Bovet et al., 2014). The purpose of the automation level is to optimize the comfort inside the building by using rules of actuation typically based on predefined threshold values (Bovet et al., 2014). The automation or supervisory level includes different types of automatic control sequences. Devices that implement these algorithms tend to be general-purpose, programmable controllers and they operate on the data provided by the field level (Wang et al., 2011) (Nývlt, 2011). The dominant network technologies used in this level are BACnet and KNX. At the top of the figure, we find the management level. This level offers applications for configuration and data visualization (Bovet et al., 2014). According to Wang et al. (2011), this level focuses on data or file transmission rate and the available bandwidth of the network. Additional functions of the management level include communication with controllers, monitoring, alarm annunciation, trend logging and statistical analysis, centralized energy management functions, and communication with, or coordination of, dedicated non-HVAC systems such as fire alarm and security control (Nývlt, 2011). Personal computer workstations are the most used devices at this level (Nývlt, 2011).

Most BMSs will change during the lifetime of the building, adding and removing input and output units at all the three levels as needed. Being able to do this without changing the main infrastructure of the BMS is a prerequisite in having a functioning, sustainable system. Using adaptable and scalable communication protocols and communication devices is probably the most important to implement in this regard. The next sub-chapter will introduce communication protocols and explain the most important devises and measures in the BMS protocol area.

3.2 Communication Protocols

Communication protocols or just protocols is going to be a well-used term in this thesis and therefore needs to be defined thoroughly. ISO (2004) defined a protocol as "the set of rules and formats regulating the information exchange between the elements of a system, including the specification of requirements for the application" (ISO, 2004, p. 30). In the light and building context, one can more specifically define a protocol as "a set of standard rules - the syntax, semantics, and synchronization - for communicating over a computer network or a lighting control system or both" (Illuminating Engineering Society, 2011, p. 3). Illuminating Engineering Society (2011) further stated that the protocol defines the methods for data representation, signalling, authentication and error detection to ensure control or enable the connection, communication, and data transfer between computing or control endpoints and that protocols may be implemented by hardware, software, or a combination of the two. At the lowest level, a protocol defines the behaviour of a hardware connection (Illuminating Engineering Society, 2011). Simply said, a protocol is a language. A set of communication rules so people, or in this case devices, can "talk" to each other.

As experienced when speaking to industry actors during this thesis' writing period and as stated in Illuminating Engineering Society (2011), more than one protocol is commonly involved in the process of taking user (or sensor) input and providing the intended response. "In any large, integrated building controls project, multiple protocols may be used in different parts of the project. Even a standalone lighting control solution might combine, for example, DALI to implement addressable dimming at the individual fixture level with BACnet to provide integration with other building systems (such as HVAC). To ensure proper system operation, the specifier needs to be aware of which products use which protocols" (Illuminating Engineering Society, 2011, p. 3). According to Goldschmidt (2007), the collection of protocols that are uniquely combined into a given product is called the "protocol stack". The usage of multiple protocols and the consequences of this will be covered in this sub-chapter and also in the subsequent chapters of this thesis. The aim of this sub-chapter is to explain the most important aspects of communication protocols in building management in a clear and logical way.

3.2.1 The OSI Model

"The Open System Interconnection (OSI) Basic Reference Model (ISO 7498) is an international standard that defines a model for developing multi-vendor computer communication protocol standards. The OSI Model addresses the general problem of computer-to-computer communication and breaks this very complex problem into seven smaller, more manageable sub-problems, each of which concerns itself with a specific communication function. Each of these sub-problems forms a "layer" in the protocol architecture" (Wang, 2010, p. 78).

The OSI model consists of seven layers of network architecture (the flow of information within an open communications network), with each layer defined for a different portion of the communications link across the network (Sinopoli, 2010). The layers of the model are shown in Figure 3.4 on the next page, along with arrows visualizing that the communication is two-way and for both sending and receiving data. The figure illustrates the full and a simplified OSI model. The simplified model has merged some of the layers together, making the model more easily understood. The seven layers of the OSI model are frequently referred to as Layer 1-7 counting from the bottom (the physical layer) to the top (the applications layer) instead of using the name of the layers.

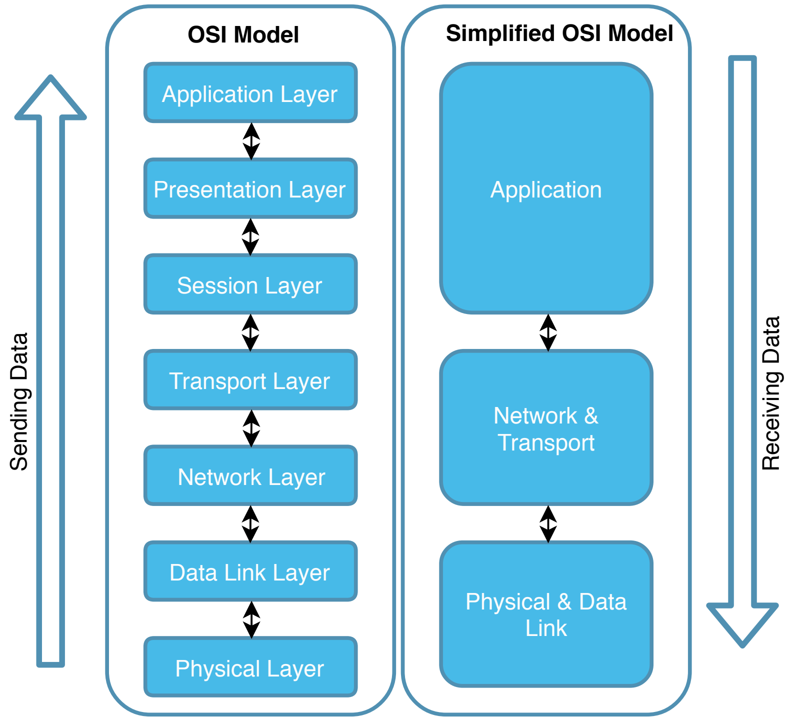

Figure 3.4: The full and simplified OSI model (Silvair, 2018)

The data transmission can be initiated by a network device or an administrator at the top layer. The data then moves from the highest to the lowest layer to communicate the data to another network device or user. To complete the communication, the data travel from the lowest to the highest layer. When a data packet moves from the bottom to the top of the model, each layer takes the data of the preceding layers and adds its own information or header to the data. One can say that each layer puts its own "envelope" around the preceding "envelope". When data moves from top to bottom, each layer removes its information or "envelope" from the data packet. (Sinopoli, 2010)

The first layer is the **Physical Layer** which specifies the electrical, optical, or radio signalling, and the mechanical or physical connections to the medium type in use. This layer provides a physical path for electrical signals representing bits of transmitted information and defines the characteristics of these signals, such as voltage and current levels, frequencies and timing. The physical layer specifies the mechanical properties of network cables and connectors and is the only real interconnection between the network nodes. (Wang, 2010)

The second layer is the **Data Link Layer** which provides error-free transfer of data frames from one node to another over the physical layer (Microsoft Support, 2017). This layer transfers the bits into so-called "frames" to guarantee reliable transmission. It is added a source and destination address to the data stream as well as information to detect and control transmission errors. The data link layer has two sublayers, the Logical Link Control (LLC) sublayer, which maintains the communications link between two devices on the network, and the Media Access Control (MAC) sublayer which manages the transmission of data between two devices. MAC addresses is a well-known term among computer professionals and all devices connected to an internet network has a unique address, a MAC address. (Sinopoli, 2010)

The **Network Layer** routes data packets through the network, deals with network addressing and determines the best path to send a packet from one network device to another. The Internet Protocol (IP) is the most known example of a network layer implementation. The **Transport Layer** is responsible for reliable transport of the data and breaks, simplifies and sequence the upper-layer data packets. The Transmission Control Protocol (TCP) is currently the major transport protocol and is typically used with the IP, then referred to as TCP/IP. (Sinopoli, 2010)

The **Session Layer** provides a method by which two systems may organize and synchronize their dialogue, and therefore manage the exchange of data between themselves. The session layer is probably the most complex of the layers. The **Presentation Layer** is concerned solely with the presentation of data while the data is in transit. The presentation layer provides character code translation, data conversion, data compression and data encryption (Microsoft Support, 2017). (Wang, 2010)

The **Applications Layer** does not represent the actual application (as the name implies), but is the application protocol (Wang, 2010). The layer provides the application itself with a gateway to the communications environment (Wang, 2010). The session, presentation and application layers are often considered as one layer. Sinopoli (2010) wrote that the session and presentation layers manage the dialogue between end-user applications, then format and deliver the data to the application layers. The session layer establishes, manages, and terminates the connection between the local and remote application and the presentation layer establishes a data framework between the application layer entities (Sinopoli, 2010). According to Silvair (2018) the application layer is the key to interoperability: “If the application layer is not defined, devices simply won’t be aware of the context of communication, and will never understand each other unless this is somehow agreed between vendors of particular products. This explains why the problem of interoperability relates not only to situations where two devices employing different protocols can’t communicate. The thing is that even if they share the same protocol, they still might not be able to interoperate if that particular protocol doesn’t define the topmost layer of the OSI model” (Silvair, 2018, p. 7).

Silvair (2018) further describe that some of the protocols (or standards) aspiring to connect the IoT define only a small part of the OSI model while relying on other available technologies to take care of the remaining aspects of communication while others go all the way from the physical layer up to the application layer. This means that all the layers of the OSI model do not have to be defined or realized in a communication protocol - the OSI model is a reference model and not a law. Silvair (2018) further stated that, by itself, this does not make any of the protocols better or worse and that different applications have different requirements. There is no one-size-fits-all solution. Silvair (2018) (and many others) uses a simplified version of the OSI model, which in many cases of the scope of the IoT (and this thesis) is detailed enough. This simplified model is also shown in Figure 3.4 and has merged the physical and data link layer together, the network and the transport layer together and the three layers at the top together. In the future chapters of this thesis this simplified model will be used when possible.

Sinopoli (2010) stated that the discussion of system integration should be framed using the OSI model, focusing on the physical, data, network and application layers and that doing so adds clarity and understanding to both industry and client discussions. Connecting the OSI layers to the three levels of BMSs is also of interest. In this regard, it can be stated that as opposed to the mainly theoretical context of the OSI model, the BMS levels is more physical. The layers of the OSI model can be found in the protocols used in the networks of the different building management levels. In Sub-Chapter 3.3, the most important communication protocols in light and building management will be presented. Here it will come evident that some protocols encapsulate all layers of the OSI model, while others only the bottom layers of the model and that several protocols are frequently used together in a BMS.

3.2.2 Important Technological Devices and Terminology

Technological devices such as hubs, bridges and gateways are important in the building management protocol context because they are inevitable in making functioning networks. These devices work on one or several of the levels of the OSI model and according to Rexford (2009), the different layers switch different "things". The physical layer switches electrical signals and is operated by repeaters and hubs. On the data link layer, frames are the name of the switched data and bridges and switches operates on this layer. The network layer switches packets and routers operates here. A gateway is a device that operates on the higher layers of the OSI model, transport gateways on the transport layer and application gateways on the application layer. (Rexford, 2009)

A **network** in the IT context is according to Christensson (2018) multiple devices that communicate with one another. "It can be as small as two computers or as large as billions of devices. While a traditional network is comprised of desktop computers, modern networks may include laptops, tablets, smartphones, televisions, gaming consoles, smart appliances, and other electronics" (Christensson, 2018). In a building automation network, the devices of the network will be the technical devices in a building and the connected devices. Networks are often characterized by its size, and in this thesis, it is distinguished between Local Area Network (LANs), Wide Area Networks (WANs) and Personal Area Networks (PANs).

A **LAN** connects network devices over a relatively short distance and a networked office building, school, or home usually contains a single LAN. Sometimes one building will contain a few small LANs, and occasionally a LAN will span a group of nearby buildings. In addition to operating in a limited space, LANs are typically owned, controlled, and managed by a single person or organization and tend to use certain connectivity technologies, primarily Ethernet and Token Ring. A **WAN**, on the other hand, does as the name implies, span a large physical distance. A WAN is a geographically-dispersed collection of LANs and the Internet is the largest WAN, spanning the Earth. Routers are the network device that connects LANs to a WAN. The most important difference between LANs and WANs is that most WANs are not owned by any organization but rather exist under collective or distributed ownership and management. (Mitchell, 2017)

A third type of network is PANs. A **PAN** is a computer network organized around an individual person, and that's set up for personal use only. A PAN transmits information between devices that are nearby instead of sending that same data through a LAN or WAN before it reaches something that is already within reach. PANs can be wired or wireless. Universal Serial Bus (USB) and FireWire often link together wired PANs, while Wireless PANs, (WPANs), typically use Bluetooth or infrared connections. WPANs generally cover a range of a few centimeters up to 10 meters and can be viewed as a special type (or subset) of LANs that support one single person instead of a group. Mitchell (2018a) writes that "Although PANs are, by definition, personal, they can still access the internet under certain conditions. For example, a device within a PAN can be connected to a LAN which has access to the internet, which is a WAN. In order, each network type is smaller than the next, but all of them can ultimately be intimately connected". (Mitchell, 2018a)

One of the most simple networking devices is repeaters. A **repeater** continuously monitors electrical signals on each LAN and join LANs together by transmitting an amplified copy of the given signals (Rexford, 2009). While a repeater is a two-port device a **hub** is a multiport device and can be called a multiport repeater. Hubs are fundamentally used in networks that use twisted pair cabling to connect devices and are frequently used in the star topology (Certiology, 2018a) (Star topology: See Figure 3.5). The largest limitation of repeaters and hubs is that each bit is sent everywhere (Rexford, 2009). This limits aggregate throughput and uses unnecessary computational power.

A **bridge** is a computer networking device that connects two or more LANs at the data link layer (Rexford, 2009). The bridge extracts the destination address from the frame, looks up the destination in a table and forwards the frame to the appropriate LAN segment (Rexford, 2009). A **switch** is essentially the same as a bridge but is typically used to connect hosts (i.e. computers) not LANs (Rexford, 2009). A **gateway** is a device designed for interfacing between two communication networks that use different protocols. According to Illuminating Engineering Society (2011), a gateway may contain devices such as protocol translators, impedance matching devices, rate converters, fault isolators, or signal translators as necessary to provide system interoperability and requires the establishment of mutually acceptable administrative procedures between both networks. The last device to be introduced is the **router**. According to ISO (2004), a router is a device that connects two or more networks at the network layer and a typical application is the collection of LANs.

Connecting the concepts more up to the IoT again leads to the introduction of words such as **GUI** and **API**. A Graphical User Interface (GUI) is according to Illuminating Engineering Society (2011) a screen-based, pictorial or diagrammatic representation of a system and is a point of contact between the system and the user. An Application Programming Interface (API) is an interface for developers and is an essential part of creating ecosystems of interoperable devices and services (Rowland et al., 2015). The API might be the enterprise's own frontend web or mobile apps or third-party services that interact with the system (Rowland et al., 2015).

3.2.3 Important Protocol Measures

Important protocol measures in the BMS setting is whether the data transmission goes through wires or not, what topology it has and the bandwidth, range and power consumption of the protocol. In this sub-chapter, these measures will be presented and defined, without any mentioning of a preferred or optimal value of the given measures.

Protocols can be **wired** or **wireless**. A wired protocol sends signals through wires (cables) while a wireless protocol sends signals at specific frequencies of the electromagnetic spectrum. Twisted pair cable, coaxial cable, Ethernet cable (often CAT5 or CAT6) and fiber optic cables are usual cable types used in building management applications. Wireless protocols use the radio frequency band to communicate and the 868 MHz and 2.4 GHz band is the most frequently used bands for wireless communication protocols in Europe. These bands are used because they are the only legitimate bands to use for such applications.

One of the most discussed features of protocols is whether the protocols are **proprietary** or non-proprietary i.e. **open**. "Open protocols are standards that are publicly available and are developed in an open consensus process under the auspices of a recognized (typically not for profit) organization. It is possible that some proprietary Intellectual Property may be associated with the standard, but usually it can be licensed for a reasonable royalty fee or other licensing agreement. Otherwise, such standards can be freely used - any costs are to cover development and administration. Proprietary protocols may be freely available or may be only implemented through a contract. They are normally developed by manufacturers or individuals, and therefore not developed in an open consensus method" (Illuminating Engineering Society, 2011, p. 3). ISO (2004) defines a proprietary protocol as a company-specific communication method, protected by intellectual property rights. The ISO standard also stated that proprietary protocols can be subject to special licensing agreements which have to be considered in using these protocols.

According to Illuminating Engineering Society (2011), **topology** is the physical or theoretical relationship among the network components. The topology describes the interconnections of elements in a network (devices, links, nodes etc.) that are linked together for communication and one distinguish between physical and logical topologies (Illuminating Engineering Society, 2011). Illuminating Engineering Society (2011) further stated that physical topologies represent the wiring of elements where the geometrical shape the wires forms is the base of the topology classification while logical topologies model the data flow between elements. Figure 3.5 below shows the most important topology types in the current (and future) BMS landscape.

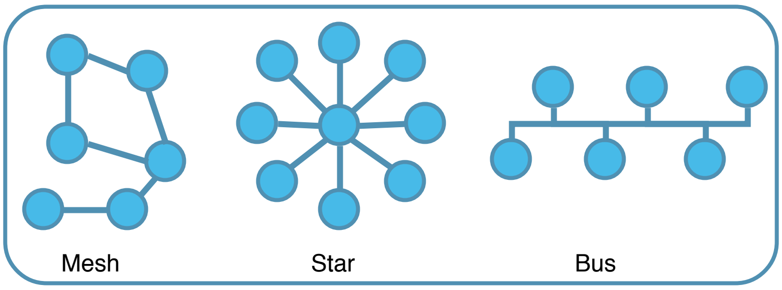

Figure 3.5: Important topologies

In wireless protocols, mesh networking is often preferred because it lengthens the overall range of the network. According to Illuminating Engineering Society (2011), mesh is a type of networking wherein each node in the network may act as an independent router, regardless of whether it is connected to another network or not. “It allows for continuous connections and reconfiguration around broken or blocked paths by “hopping” from node to node until the destination is reached. A mesh network whose nodes are all connected to each other is a fully connected network. Mesh networks differ from other networks in that the component parts can all connect to each other via multiple hops. Mesh networks are self-healing: the network can still operate when one node breaks down or a connection goes bad. As a result, the network may typically be very reliable, as there is often more than one path between a source and a destination in the network. Although mostly used in wireless scenarios, this concept is also applicable to wired networks and software interaction” (Illuminating Engineering Society, 2011, p. 9).

In the star topology, all the data is connected to a central hub. The star topology is for instance used in Wireless Fidelity (Wi-Fi) networks. One of the most used topologies in wired networking in building management is the bus topology. In the bus topology, nodes are connected to a single, central data or control source such that information does not need to pass through successive nodes, although all nodes are fed by a common signal (Illuminating Engineering Society, 2011). The “main cable” is branched out to reach the nodes in the network. This topology is cost-effective but holds limitations like difficulty of error detection, data reflection and data collision. (Certiology, 2018b)

In order to avoid any possible confusion, the term fieldbus also has to be defined. According to Wang (2010) the term fieldbus is used in the industrial and building automation industries to signify a network consisting of computers, particularly controllers and devices mounted in the “field” (various locations). Disregarded that a fieldbus network can have a physical or logical bus topology the term has nothing to do with the bus topology.

According to Fisher (2018), the term **bandwidth** has a number of technical meanings but since the popularization of the Internet, the term has generally referred to the volume of information per unit of time that a transmission medium (like an internet connection) can handle. Protocols transmit data, and the speed of data transmission is inherent characteristics of the given protocols. Some protocols have various communication media choices (KNX has for instance 4 different main choices of communication media (See Sub-Chapter 3.3.3)). Bandwidth is typically expressed in “bits per second” and abbreviated bps or bit/s. To get some reference point, a 2 hour long HD movie is about 5 GB (GigaByte). One Byte equals 8 bits, meaning that the movie is 40 Gbits. Downloading this movie would, for instance, take 40 seconds to download in a 1 Gbit/s bandwidth network. Comparing this to the size of a normal signal in building automation which is in the size range of 1-100 bits (DALI sends 16-bit packages) you will need a bandwidth in the kbit/s range for getting the signals transferred in less than a second. Closely connected to bandwidth is latency. “The term **latency** refers to any of several kinds of delays typically incurred in the processing of network data. A low latency network connection is one that experiences small delay times, while a high latency connection suffers from long delays” (Mitchell, 2018b). Latency is typically measured in seconds.

Range is not anything specific in this context. The range is simply the maximum distance data can transfer within a protocol. The range of a wireless protocol will vary according to the room structure, wall thickness, wall material and so on, while wired protocols have a more constant range. The **power consumption** of a protocol is an important aspect of BMS. Since minimizing energy usage often is the main objective of BMSs, one would certainly want a power efficient system. Power usage among the protocols is varying and it is especially important to monitor the power usage of the wireless protocols since these protocols run on batteries.

3.2.4 Interoperability

Interoperability is an essential attribute of communication protocols. This sub-chapter starts answering SQ (b): "What is interoperability and why is it important?", and will define the concept and assess the most important factors relevant to the scope of this thesis.

Interoperability in IT refers to the ability to transfer and render useful data and other information across systems, applications and components (Rowland et al., 2015). It is the ability for devices, applications and services to interact with other devices, applications, and services from different vendors, regardless of hardware architecture or type of software (Rowland et al., 2015). Interoperability in BMSs is according to ISO (2004) the capability of devices of different types and from different manufacturers to exchange information and commands via the communications network. As stated in the introduction of this thesis, interoperability is critically important to capturing maximum value and is on average required for 40 % of the potential value across IoT applications (McKinsey Global Institute, 2015). There have not been found exact numbers of how important interoperability is in BMSs, but there is no doubt that interoperability is an essential attribute of BMSs as well.

"Much of what we currently call the "Internet of Things" is not yet much like the rest of the Internet: a network of networks based on open standards. The proliferation of different technical standards means that getting devices to work together is hard. Many devices are locked away in proprietary ecosystems, because frequently that is the easiest way to get them to work. But their lack of interoperability with other devices and systems is seriously limiting its potential value and usability. Users will expect devices to work together, but right now many do not" (Rowland et al., 2015, p. 381).

The IoT is currently at the same stage as the Internet were in the 1980s with numerous closed networks that do not interoperate. Rowland et al. (2015) stated that businesses often think that their interests are best served by keeping their technology proprietary and non-interoperable. This is often right in the short term, but in the long term, interoperability helps grow the overall size of the market, which is good for everyone. The IoT is on track to become more interoperable, but the process of getting there will take time, due to both technical and competing corporate interests. (Rowland et al., 2015)

In the building landscape, there are differing networking and data standards because the different systems were optimized around the needs of the particular market, at a time where there was no conceivable need to share data with other types of systems (Rowland et al., 2015). This is the main problem in getting a functioning IoT stack for buildings and it looks like it is taking some time in getting to the "World Wide Web" interoperability stage. The development of common standards is taking unnecessary time because large enterprises who already have a competitive advantage with their own proprietary solutions is slowing down the process on purpose (Conversation, Laboratory Manager, 2018). Interoperability is the main objective for most of the smaller enterprises entering the IoT landscape since these enterprises do not have the capabilities to create a complete technology stack. Interoperability in the BMS context beams interoperability between the different protocols in the system. The OSI model is a good reference tool in the construction of interoperable protocols and ISO (2004) emphasizes that a communications protocol should be structured in layers referring to the concept of the OSI model.

Many argue that interoperability in the applications layer is the most important in the IoT context (Silvair, 2018). This is because this layer connects the different systems together. The master's thesis "Interoperability at the Application Layer in the Internet of Things" written at NTNU during spring 2015 discusses this in detail (See: Oen (2015)). Rowland et al. (2015) also discussed this and stated that at present, each IoT device type has to be controlled via a separate manufacturer's software platform, with its own frontend app, and often no API to talk to the IoT device types. Users of the BMS will not be satisfied if they have to operate ten different APIs with no global optimization. We are far beyond this point and a BMS which uses several communication protocols must have seamless interoperation between the different protocols.

The next sub-chapter will present the most important communication protocols in building management, only looking at lighting at the field level. A total of 12 protocols will be introduced, highlighting the fact that there are currently too many protocols in BMSs and emphasizing the importance of interoperability.

3.3 Protocols in Building Management

This sub-chapter presents the most used protocols in building management and provides important characteristics of the protocols. For each protocol, the connection type, openness, range, topology, bandwidth, OSI layers and the typical BMS levels will be stated. This chapter could have included other protocols and compared other important measures and some scholars might feel that "their" protocol is not included in this section. Which protocols to include were based on the preliminary literature review, interview/conversations with Glamox employees and the general trends in the technological environment.

3.3.1 BACnet

BACnet is according to Wang (2010) a data communication protocol for BA and control networks. BACnet relates specifically to the needs of BA equipment and is used extensively in BMSs throughout the world. "BACnet has been developed under the auspices of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). It is an American national standard, a European standard, an ISO global standard and the national standard in more than 30 countries. The protocol is supported and maintained by ASHRAE Standing Standard Project Committee 135. It is the only open protocol that was designed originally for BA from the ground up, and it is an open protocol that supports high-end functions such as scheduling, alarming and trending" (Wang, 2010, p. 74).

BACnet is focused on the management and automation level and is a completely non-proprietary object-oriented system (Nývlt, 2011). As many other communication protocols, BACnet employs the OSI model as its reference model (Wang, 2010). The protocol is based on a four-layer collapsed architecture that corresponds to the physical, data link, network, and application layers of the OSI model as shown in Figure 3.6. As can be seen from the figure, the application layer and a simple network layer are defined in the BACnet standard while the various options in the data link and physical layer are defined by other communication protocols. On the two lowest levels of the OSI model, the protocol is very flexible, because one can presently choose from a very incompatible group of data link/physical layers (Nývlt, 2011).

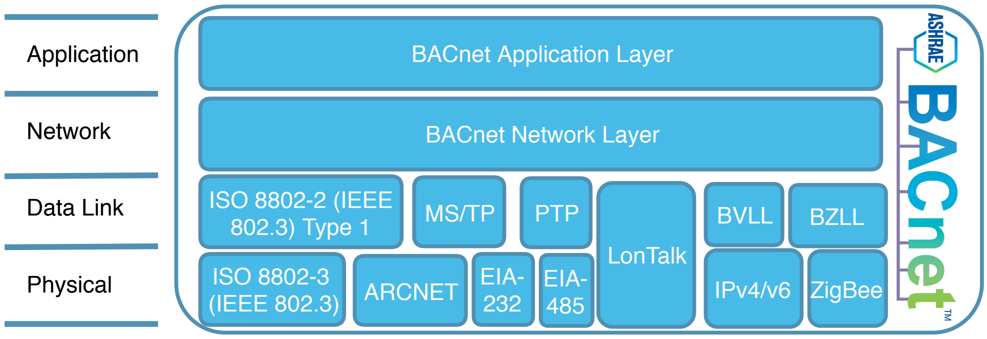

Figure 3.6: BACnet OSI layers (ISO, 2017, p. 11)

The choice of only using selected layers of the OSI model are according to Wang (2010) adopted by BACnet to reduce message length and communication processing overhead and permits the BA industry to take advantage of lower cost, mass-produced processors. Wang (2010) further stated that the BACnet committee spent a lot of time on deciding which connection options that should be available at the physical level and that each of which fills a particular niche in terms of the price–performance trade-off. Ethernet (IEEE 802.3) is the fastest connection choice at the physical level with a bandwidth of 10-1000 Mbit/s. Ethernet is also likely to be the most expensive choice in terms of cost per device. Next comes ARCNET at 2.5 Mbit/s, followed by the hard-wired EIA connections which use a dial-up or "point-to-point" protocol called PTP. For devices with lower speed-requirements, BACnet defines the master–slave/token- passing (MS/TP) network designed to run at speeds of 1 Mbit/s or less over twisted-pair wiring. BACnet also has the possibility to use the LonTalk, the IPv4 or v6 and the ZigBee protocol at the physical/data link layer. These protocols will be explained in the subsequent sub-chapters. Wang (2010) stated that a key point is that BACnet messages can, in principle, be transported by any network technology, if and when it becomes desirable to do so. (Wang, 2010)

3.3.2 LonTalk and LonWorks

LonWorks is an automation platform which uses the standardized communication protocol, LonTalk, developed in the late nineties by the company Echelon. In opposite to BACnet, LonWorks with LonTalk were not developed primarily for the purposes of building automation, but as a universal automation platform. Because of this, LonWorks is a very flexible and complex automation system which is currently used not only for building automation but also in train and subway control, industrial production control etc. Nývlt (2011) further stated that the LonWorks platform is focused mainly on the automation and field level. The main disadvantage of the LonTalk protocol is that it is dependent on the use of the proprietary Neuton chip. (Nývlt, 2011)

The protocol follows the layered architectural guidelines of the OSI model as shown in Figure 3.7 below. Wang (2010) stated that the physical layer is typically implemented using the transceiver from the LonWorks group and that there are many options available for different LAN speeds and physical media. A LonWorks LAN can be built using most types of LAN cables, including twisted pair, coaxial, powerline and fibre optics, as well as radio frequency and infrared connections. The layers between the data link layer and presentation layer are implemented using a Neuron chip. (Wang, 2010)

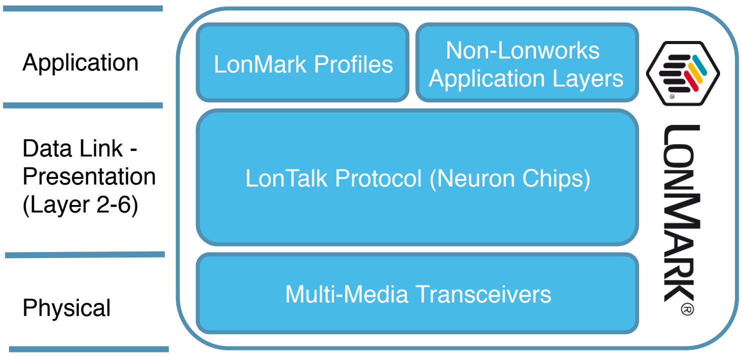

Figure 3.7: LonTalk OSI layers (Wang, 2010)

The LonWorks platform can according to Nývlt (2011) manage almost every task and wish in building and home automation (BMS) from room temperature control to security and access control systems. Nývlt (2011) further claims that because of the cost of devices, LonWorks (similarly to KNX) is still not much suitable for “normal” family houses. In the general literature and in the trade fair in Frankfurt, the impression is that the LonWorks platform is not used in today’s BMSs. Glamox had luminaires supporting LonWorks when it first arrived, but the cost of implementing the proprietary components made the system expensive and the “LonWork-luminaires” was taken off the market after a short period (Conversation, Laboratory Manager, 2018).

3.3.3 KNX

KNX, short for Konnex resulted from the merger of the bus systems European Installation Bus (EIB), BatiBUS and European Home System (EHS) in order to create a single European standard (Bellido-Outeirino et al., 2012). KNX is an international (ISO/IEC 14543-3), Chinese and US standard and a totally open protocol (Bellido-Outeirino et al., 2012). KNX is still in many environments in Europe called EIB and bus devices can either be sensors or actuators needed for the control of building management equipment such as: lighting, blinds/shutters, security systems, energy management, heating, ventilation and air-conditioning systems, signalling and monitoring systems, interfaces to service and building control systems, remote control, metering, audio/video control, white goods, etc (KNX Association, 2014).

There exist four choices of physical communication media of the protocol according to KNX Association (2018):

1. *Twisted Pair (TP).* This is the most used communication media in the KNX protocol, often called KNX TP1 (Wang, 2010). Bitrate of 9600 bit/s. Line topology, max 64 devices per line. Several length restrictions: max 350 m from power supply to device, max 700 m between two devices on a line, max 1000 m length of a line segment. Twisted Pair installations are typically limited to 500 m per bus (Illuminating Engineering Society, 2011).

2. *Powerline (PL).* Bitrate of 1200 bit/s. Line topology. The basic unit of an installation is a line containing 255 devices.

3. *Radio Frequency (RF).* Telegrams are transmitted in the 868 MHz (Short Range Devices) frequency band, with a maximum radiated power of 25 mW and bitrate of 16.384 kbit/s. "The devices in a KNX RF installation do not need to be arranged hierarchically, and can be installed virtually anywhere. Provided that they are within range of one another, any sensor can communicate with any actuator" (KNX Association, 2018, p. 12).

4. *IP (Ethernet).* KNX telegrams can also be transmitted encapsulated in IP telegrams (More about IP and Ethernet in Sub-Chapter 3.3.8.

Not all layers of the OSI protocol are necessary for the KNX protocol. According to Köhler (2008) layer 1, 2, 3, 4, and 7 is used by the KNX standard. The KNX standard is also usable in all layers of BMSs.

3.3.4 DALI

The most common protocol in lighting control today is the DALI protocol. DALI is an acronym for Digital Addressable Lighting Interface and is an industry-wide open digital protocol for the commercial lighting market (Artistic Licence Engineering Ltd., 2018). DALI is according to DiiA (2017) a dedicated protocol for digital lighting control that enables easy installation of robust, scalable and flexible lighting networks. DALI have more options than the classical 1-10 V analog control like broadcasting (all devices on the bus), group and individual control and can be reconfigured by software reprogramming. Different lighting functions and moods can be achieved in different rooms or areas of a building, and then easily adjusted and optimized (DiiA, 2017). Two-way communication is possible with DALI, meaning that a device can report a failure or answer a query about its status etc. (DiiA, 2017). The DALI control cable (called the DALI line or DALI bus) exists of 2 polarity insensitive wires with a +/- 16 V potential between the wires (Philips, 2008). "By changing the voltage between 0 and 16 V a digital signal is created. The DALI signal exists of two parts, a "where to" byte and an "info" byte" (Philips, 2008, p. 6).

The maximum wire length of a DALI line is 300 meters with a maximal voltage drop of 2 V (Ńývlt, 2011). The maximum number of connected devices to one line is 64 (master and slaves) and there is also a restriction of maximum 16 groups of devices and maximum

16 light scenes (Nývlt, 2011). The topology of a DALI line is absolutely free (Nývlt, 2011). There exist a gateway to almost every important building and home automation system, bus or protocol and one can also use a modular PLC used as an Ethernet gateway for DALI or to connect DALI with EnOcean and other protocols (Nývlt, 2011). According to the Sales Director LMS, DALI is a very slow protocol (Interview, Sales Director LMS, 2018). A bandwidth of 1.2 kbit/s is not much but it is sufficient for the current amount of data transfer in digital lighting. If one wants to expand the amount of data transferred i.e. use the protocol to transfer for instance video monitoring data, this bandwidth will not be enough.

In the sense of the OSI model, the DALI protocol itself belongs to all the layers of the reference model. But it is just for lighting applications. This means that the application layer of the protocol only relates to lighting. According to Rubinstein et al. (2003) DALI, as it is currently implemented, does not accommodate communication with or between devices other than ballasts and lighting controllers, and does not provide a link to other elements of the building control system.

3.3.5 Bluetooth

"Today, Bluetooth is the leading low power wireless connectivity technology used to stream audio, transfer data, or broadcast information between devices. Now, with the introduction of a mesh networking capability, Bluetooth mesh networking is poised to further catalyze beacons, robotics, industrial automation, energy management, smart city applications, and other industrial IoT and advanced manufacturing solutions" (Kolderup, 2017).

The history of the original Bluetooth started back in 1994 when the Swedish telecommunications company, Ericsson, came up with the idea of replacing the tangle of RS-232 cables that were then commonly used to communicate between instruments with an RF-based "wireless" alternative. At the same time the other telecommunication companies Intel, Nokia, Toshiba and IBM worked on linking cellphones and computers and the companies realized that to have any chance of universal interoperability, the technology would need to be standardized and driven by a Special Interest Group (SIG). The name "Bluetooth" originates from the nickname of King Harald which brought together warring tribes from Norway, Denmark and Sweden in the 10th century. (Nordic Semiconductor, 2014)

The Bluetooth protocol has developed a lot since the beginning in 1994 and in 2016 Bluetooth 5 was introduced. This protocol has a maximum data rate of 2 Mbit/s and can be twice as fast as the previous versions of Bluetooth. In July 2017 Bluetooth Mesh specifications were officially published for the world. According to Silvair (2018), Bluetooth Mesh is very different from the mesh technologies used in, for instance, Z-wave and ZigBee. Bluetooth Mesh uses an approach called managed flooding where each message is broadcast to every device in range and relaying nodes push it deeper into the network by broadcasting it, again, to all devices within their reach. Bluetooth Mesh is a topology instruction set and is based in Bluetooth Low Energy (BLE) which requires only Bluetooth 4.0 (can also be used on Bluetooth 5) (Midttun, 2017). Bluetooth operates at the 2.4 GHz frequency band and uses an adaptive frequency hopping scheme which allows the signal to hop dynamically between the 40 available channels in the frequency spectrum. According to Silvair (2018) this is particularly important since Bluetooth utilizes the same 2.4 GHz spectrum as numerous other radio technologies, including Wi-Fi, but also appliances such as microwave ovens, baby monitors or cordless phones. The range of Bluetooth is about 20-50 meters, and scholars claim that with Bluetooth 5 it can be 4 times longer (Semiconductor, 2018) (Heukelman, 2017). The Bluetooth protocol belongs to all the layers of the OSI model, as can be seen from Figure 3.8 below. (Silvair, 2018)

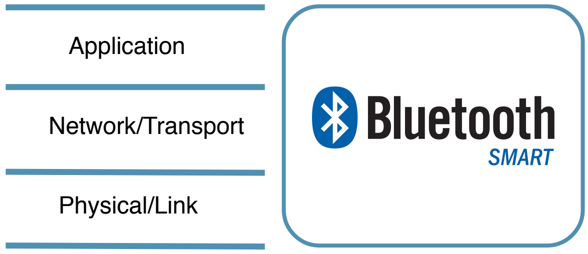

Figure 3.8: Bluetooth OSI layers (Silvair, 2018, p. 31)

At the Light + Building trade fair, many of the exhibitors used their own proprietary solution based on the Bluetooth technology. There was also many who used the Casambi solution (See: Casambi (2017)). This is a proprietary solution based on Bluetooth LE with their own mesh network. The fact that many actors have implemented their own Bluetooth network topology highlights the need for the entrance of the Bluetooth Mesh topology. Throughout this thesis, Bluetooth and Bluetooth Mesh will be used interchangeably. When referring to Bluetooth (or Bluetooth Mesh) in this thesis it is referred to BLE with the mesh topology unless something else is stated.

3.3.6 ZigBee

ZigBee is a suite of high-level communication protocols using small, low-power digital radios based on the IEEE 802.15.4 standard for WPANs. Their vision is for all lighting fixtures, sensors and switches to communicate wirelessly, without the need to add expensive cabling to buildings. The ZigBee protocol is suited for RF applications that require a low data rate, long battery life, and secure networking. According to Illuminating Engineering Society (2011), ZigBee's current focus is to define a general-purpose, inexpensive, self-organizing mesh network that can be used for industrial control, embedded sensing, medical data collection, smoke and intruder warning, building and home automation (including lighting). (Illuminating Engineering Society, 2011)

ZigBee uses a very small amount of power and individual devices can run for one-two years using the originally installed battery (Illuminating Engineering Society, 2011). The ZigBee protocol operates at the 868 MHz frequency band in Europe and has a maximum bandwidth of 250 kbit/s (Silvair, 2018). Depending on power output and environmental characteristics, the maximum range is about 20 meters between individual modules of the network (Silvair, 2018). As the protocol is structured to transfer small amounts of data relatively slow, this protocol is best suited at the field level of a BMS.

Figure 3.9 on the next page illustrates that the protocol is built on top of the IEEE physical radio specification standard 802.15.4 and that the ZigBee protocol stack defines the network, transport and application layers of the OSI model. According to Silvair (2018), IEEE's 802.15.4 standard is supported by multiple silicon vendors, including the biggest brands in the industry, which creates a healthy competition environment that naturally benefits their clients. The ZigBee technology is an open global standard and while the protocol does support other topologies, it is the mesh networking capability that was the key to ZigBee's market success. ZigBee uses destination-based routing to deliver packets to individual nodes of the network which means that mobile controllers frequently changing their location, burnt-out smart bulbs, or any other devices that suddenly go down for whatever reason are not a problem for ZigBee, as its self-healing network can quickly reroute data packets to ensure they reach destination should any of the nodes fail (Silvair, 2018).

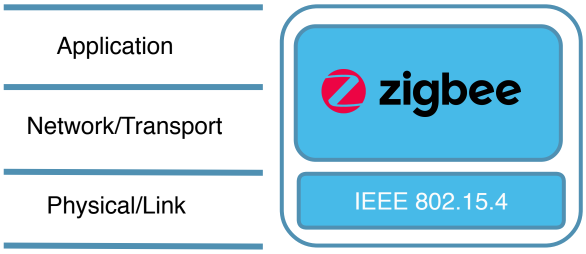

Figure 3.9: ZigBee and IEEE 802.15.4 OSI layers (Silvair, 2018, p. 20)

3.3.7 Z-Wave

The Z-Wave protocol is a proprietary interoperable wireless communication protocol which is developed by the Danish company Zensys and the Z-Wave Alliance. The protocol is designed for low-power and low-bandwidth appliances such as home automation and sensor and control networks and uses an RF mesh network on the 868 MHz frequency band. There is a restriction of having maximum 232 units within a Z-wave network and one can bridge several networks together with some limitations. Z-wave units communicate at 9.6, 40 or 100 kbit/s, depending on the generation of chips and have a range of approximately 30 meters in "open air" conditions (Silvair, 2018). (Illuminating Engineering Society, 2011)

As can be seen from Figure 3.10 below, the protocol covers all the layers of the OSI model. As previously stated this is important in overcoming the problem of interoperability in the IoT and can explain why the Z-wave technology has approximately 35 million compatible units in circulation (in the residential market). (Silvair, 2018)

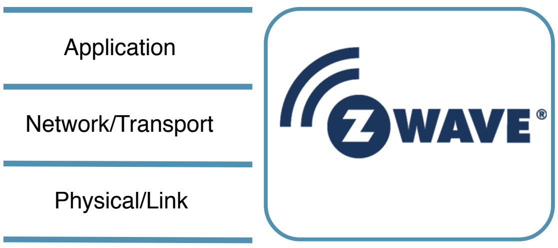

Figure 3.10: Z-Wave OSI layers (Silvair, 2018, p. 14)

3.3.8 The Internet Protocol Suite

This sub-chapter will describe the "Internet Protocols". There does not exist one single protocol that constitutes to the Internet, but instead, there are several protocols that in sum forms what we know as "The Internet". This sum is often named "The TCP/IP Protocol Suite".

The name TCP/IP is a concatenation of two major data communications protocols: The Transmission Control Protocol (TCP) and the Internet Protocol (IP). It is a ubiquitous protocol suite used by the Internet, the World Wide Web, and most networked computers for exchanging data. The TCP/IP suite defines conventions for connecting different networks and routing traffic through routers, bridges and other types of connections and includes a set of standards that specify how computers should communicate. The protocol is mature and virtually all computers capable of operating in a networked environment support it because of its reliability and universality. (Illuminating Engineering Society, 2011)

According to Fujitsu (2006) the TCP/IP protocol suite is divided into four layers which in sum constitutes the full OSI model. Figure 3.11, on the next page illustrates this but has merged the network (IP) layer and the transport (TCP) layer. At the top, we have the application layer. The protocol used here depends on the given application, but the most frequently used protocols in this layer in IoT applications are according to Rowland et al. (2015) the HyperText Transport Protocol (HTTP), and the Message Queuing Telemetry Transport (MQTT) protocol. Oen (2015) stated that the Constrained Application Protocol (CoAP) is used with constrained nodes and constrained networks in the IoT.

Rowland et al. (2015) describes these protocols in relevance to the IoT and stated that HTTP is widely supported and allows sensor networks to be explored in an easily accessible and universal way through web APIs, but that it is not the best protocol for passing data around lots of devices as it requires a direct connection to be established between any devices that need to share data. The MQTT protocol is better suited since it has been specifically designed for the IoT. This protocol prioritizes smaller data transmissions and more efficient ways of passing data around large networks of low-powered devices. (Rowland et al., 2015)

After the application layer, we find the network layer which is defined by the IP-protocol and the transport layer which is defined by the TCP protocol. The IP protocol has been claimed to be too memory and bandwidth-intensive for IoT devices and the introduction of the IPv6 Low Power Wireless Personal Area Networks (6LoWPAN) protocol is an attempt to find a more suited protocol at this layer. According to Oen (2015), 6LoWPAN comprise devices that conform to the IEEE 802.15.4-2003 standard, which describes short range, low bit rate, low power, and low-cost devices. There is also worth mentioning that some claims that the User Datagram Protocol (UDP) might be more suited to IoT applications than the TCP protocol at the transport layer (Oen, 2015). A system using these "new Internet protocols" has the IEEE 802.15.4 protocol at the physical layer, the 6LoWPAN protocol at the data link layer (together with IEEE 802.15.4 MAC protocol), the IPv6 protocol at the network layer, the UDP protocol at the transport layer and the application layer will most likely use the MQTT protocol (Olsson, 2014).

At the bottom, we have the network access layer which according to Fujitsu (2006) contains two sublayers, the media access control (MAC) sublayer and the physical sublayer. The MAC sublayer aligns closely with the data link layer of the OSI model and is sometimes referred to by that name while the physical sublayer aligns with the physical layer of the OSI model (Fujitsu, 2006). There are several protocol options in this layer. Figure 3.11 shows the Wi-Fi and the Ethernet options.

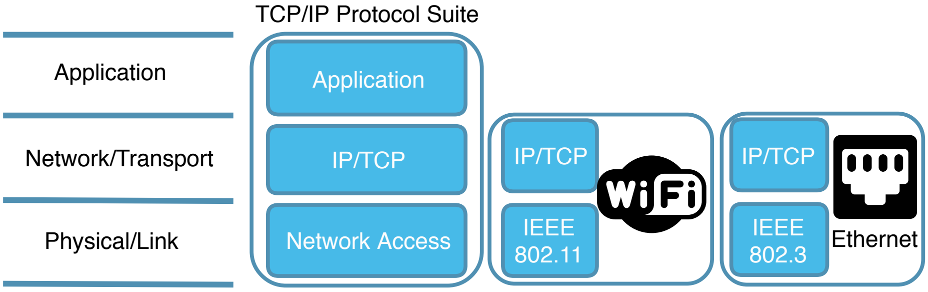

Figure 3.11: TCP/IP suite OSI layers (Rouse, 2017) (Silvair, 2018, p. 9)

According to Wang (2010), it is most common to use the Ethernet protocol (more commonly referred to as an Ethernet cable), at the physical layer of the TCP/IP suite in buildings. The Ethernet protocol is defined through the standard IEEE 802.3 which defines the physical and data link layer (MAC). Ethernet can use different wires as coaxial or optical cable which has different bandwidths and ranges. The bandwidth span of 10-1000 Mbit/s will be used throughout this thesis, even though there have been found literature stating larger amounts, such as Oen (2015). According to the Minico (2017), Ethernet uses bus or star topologies and a common maximum range of a line segment is about 100 meters.

Wi-Fi technologies, on the other hand, is based on the IEEE 802.11 protocol standard (2.4 GHz) which was designed primarily to promote LAN-based product interoperability (Wang, 2010). Wi-Fi and IEEE 802.11 is often used interchangeably in literature and the standard IEEE 802.11n is currently the most commonly used in today's homes and offices (Banerji, 2013) (Silvair, 2018). New IEEE 802.11n routers has a maximum bandwidth of 450 Mbit/s and the new IEEE 802.11ac routers have a bandwidth of 450 Mbit/s at 2.4 GHz and up to 1300 Mbit/s at 5 GHz (Mitchell, 2018c). Typical range of Wi-Fi routers is up to 50 meters indoors (Mitchell, 2018c). A Wi-Fi network has a star topology, which means that all its nodes connect directly to a central hub, e.g. a wireless router (Silvair, 2018). Figure 3.11 over also illustrates the Wi-Fi and Ethernet OSI-architecture. According to Wang (2010), Wi-Fi is primarily used for TCP/IP traffic on Ethernet connections which requires that all devices have a unique IP address. “Since wireless BAS field controllers and devices normally need very low data rates, Wi-Fi has no advantage for the applications at field level and therefore is not suitable at this level” (Wang, 2010, p. 68). This needs some further explanation. Why does not Wi-Fi fit into the IoT landscape? Wi-Fi is by the general society seen as the Internet itself. According to Silvair (2018) the Wi-Fi technology is not fitted for IoT applications (field level in BMS) for several reasons. The data transfer rate is overkill for typical smart home/office applications, the protocol is extremely power intensive and the reliance upon a central gateway to handle all the traffic is one major drawback (Silvair, 2018). One also needs to write a password to connect a device to the network, which is hard to do when your device has no keyboard or screen (e.g. sensors) (Silvair, 2018).

A third option in the link layer is to use cellular data. Cellular data uses the same data networks as the mobile, usually GPRS or 3G/4G, and makes sense to use on devices that need to move around and you can not rely on a Wi-Fi network. Cellular data requires minimal user setup but uses a lot of power and can be expensive since it requires an ongoing subscription to a network provider. (Rowland et al., 2015)

So to sum up: The TCP/IP suite (Wi-Fi, Ethernet or Cellular) is best suited at the management (and automation) level of BMSs and is therefore not seen as a main contributor to the IoT technologies. An IoT protocol needs low power consumption, easy installation, low price, "medium speed" data transmission and interoperability. The Internet protocols used today do not align well with these requirements.

3.3.9 Comparison of the Protocols

In an attempt to minimize any possible confusion for the reader, Table 3.1 was made. The table compares the important measures (described in Sub-Chapter 3.2.3) in the protocols. The table is made with the same content (and references) as the sub-chapters about the protocols. For the Internet protocol suite, the TCP/IP stack with Ethernet and Wi-Fi is compared. This is because these choices are what is currently known as the industry standards for the Internet protocol suite.

Table 3.1: Comparision of important measures in the protocols

Protocol	Wireless? Frequency in Europe	Open?	Max Range (Indoors)	Topology	Bandwidth [kbit/s]	OSI Layers	Typical BMS Levels
BACnet	Yes/No. ZigBee transmission is possible. 868 MHz	Yes	500 m with TP	Depends on communication media	9.6-1,000,000	1-3 and 7	(F), A and M
LonTalk	Yes/No. RF transmission is possible. 868 MHz	No	500 m with TP	Depends on communication media	9.6-1,000,000+	1-7	F and A
KNX	Yes/No. RF transmission is possible. 868 MHz	Yes	500 m with TP	Depends on communication media	9.6-1,000,000	1-4 and 7	F, A and M
DALI	No	Yes	300 m and max 64 nodes	Free	1.2	1-7	F (and A)
Bluetooth Mesh	Yes. 2.4 GHz	Yes	20-50m (x4 with Bluetooth 5)	Mesh	1000-2000	1-7	F
ZigBee	Yes. 868 MHz	Yes	20 m	Mesh (most used)	250	1-7	F
Z-Wave	Yes. 868 MHz	No	30 m	Mesh	100	1-7	F
TCP/IP. Wireless	Yes. 2.4 GHz	Yes	50 m	Star	450,000	1-4	(A) and M
TCP/IP. Ethernet	No	Yes	100 m	Bus or Star	10,000-1,000,000	1-4	(F, A) and M

The column “Wireless? Frequency in Europe” describes the physical layer in the OSI model of the given protocol. There is only DALI and Ethernet that has a totally wired physical layer. All the other protocols have the choice of using RF transmission either on the 868 MHz band or the 2.4 GHz band. Speaking of radio transmission, it is also desirable to mention the many proprietary radio solutions that are existing. It is not unusual that various technological devices use the 868 MHz or 2.4 GHz band with their own proprietary radio protocol. Baby monitors, for instance, has used such technologies for decades (Rowland et al., 2015). Settling for such a proprietary solution may be reliable and cheap but the devices will not interoperate with other devices and may interfere with them (Rowland et al., 2015).

The table also shows that there are mostly open protocols among the evaluated protocols. In this regard, it is worth mentioning that this was an intentional choice from the researcher’s side since there is little doubt about the fact that there is towards open protocols we are heading. The range means the maximum range between two nodes in the network, in normal conditions. From the table, we can see that the ZigBee protocol has the lowest maximum range at 20 meters while the wired solutions of the protocols at the automation and management levels has the longest ranges of potentially 500 meters. The topology column expresses that mesh, bus and star are the most used topologies and that the mesh topology is used most frequently in the wireless protocols. The bandwidth column shows that there are really large differences among the bandwidth of the protocols. The bandwidths are expressed in the same unit, kbit/s, making the comparison easier. One can see that the DALI protocol is extremely slow (almost a million times slower) compared to the protocols using the fastest Ethernet cabling.

When it comes to the OSI layers, the table shows that all the protocols support layer 1-3 and that over half of them supports all the layers. There is only Wi-Fi and Ethernet that do not support the application layer, but there exist protocols like HTTP and MQTT that interoperates with Wi-Fi and Ethernet and establishes the application layer connection. For the “Typical BMS Levels”-column it is important to emphasize that the levels expressed here are not definite, the column is showing the most frequent BMS levels of the given protocol during the writing period of this thesis.

One aspect the table fails to mention is the cost of the necessary components and the vendor availability. This will, of course, be an important decision making factor for users and enterprises in the communication protocol selection phase. Protocols operating on well-adapted technologies will often be cheaper than new and unfamiliar technologies. According to Molony (2018), the acceptance of Bluetooth Mesh in the lighting industry is expected to be driven by the low cost and ubiquity of Bluetooth modules. Ten million Bluetooth devices are shipped every single day and the technology is widely understood by engineers in the lighting industry (Molony, 2018). DALI, which is currently well accepted in the lighting industry started with a relatively high price, but has today stabilized at a competitive price and has many certified vendors. BACnet, LonTalk, KNX and the TCP/IP suite is in general seen to be expensive technologies (Conversations, Various Glamox employees 2018). Commissioning time or programming complexity is also not included in the table. These are of course important aspects to consider in the choice of protocol, but the largely varying needs and competence within the different organizations made the researcher discard such aspects from the thesis scope.

The table does not compare the power usage of the protocols. The most relevant protocols to compare in this regard is the wireless protocols and more specifically; ZigBee, Bluetooth and Wi-Fi (because of the protocols' market shares and the questionnaire results). The paper "Power Consumption Analysis of Bluetooth Low Energy, ZigBee and ANT Sensor Nodes in a Cyclic Sleep Scenario" found that the BLE protocol used less power than the ZigBee protocol for all measured sleep intervals (BLE used 10.1 μA and ZigBee used 15.7 μA) (Dementyev et al., 2013). Evidence who supports the statements made about the high power usage of Wi-Fi is for instance cited in Laukkonen (2017) and Vogler (2018). These sources stated that BLE uses about 3 % of the power of Wi-Fi to accomplish similar tasks. Based on this, there is certainly no doubt about that there are considerable differences regarding the power usage of the various wireless protocols and that Wi-Fi is an extremely energy-demanding technology compared to other available comparable technologies for IoT usage.

In this chapter, Chapter 3, the theoretical foundation for the thesis has been given. All relevant terms and concepts which are essential for understanding the subsequent chapters have been explained. When reading the remaining parts of this thesis, the readers are encouraged to use this chapter, as well as the List of Abbreviations, when stumbling into incomprehensible words or subjects. In the next chapter the case enterprise of this thesis, Glamox AS, will be presented.

Chapter 4

Case Study - Glamox AS

This chapter firstly presents the case enterprise of this thesis, Glamox AS. Secondly, a short description of their current LMSs will be given. Sub-Chapter 4.3 discusses the competitive landscape, using a short stakeholder analysis and Porter's five force model. This chapter aims to answer SQ (c): "What is the current competitive situation for Glamox AS in the IoT environment?"

4.1 Background

"Glamox is a leading supplier of lighting solutions to the professional building market, offering complete product ranges for schools, health care facilities, commercial and industrial buildings, retail facilities, hotels and restaurants" (Glamox AS, 2018a).

Glamox AS is a global enterprise producing lighting solutions for several important sectors. The enterprise was founded in 1947 by the Norwegian mechanical graduate engineer, scientist and inventor Birger Hatlebakk (Kjølås, 2009). Hatlebakk discovered a method for electrochemical surface treatment of aluminium, which he called "glamoxation". The "glamoxation" process made it possible to use an inexpensive type of aluminium to create energy efficient luminaires that emitted a pleasant light (Arc Magazine, 2017). Of course, the name of the new organization was Glamox, and a purpose-made factory was built in Hatlebakk's home town, Molde. In 1959 there were 147 employees, and a solid financial platform for further expansion had been established. (Glamox AS, 2018b)

Since then, Glamox has expanded its business throughout the whole world and has today approximately 1,300 employees (of whom 500 in Norway) and operations in 60 countries (Arc Magazine, 2017). Glamox operates in two main market arenas, the professional building market and the marine and offshore market. This is done through the divisions Professional Building Solutions (PBS) and Global Marine and Offshore (GMO), respectively. Glamox also has a third division where production, purchasing and logistics are coordinated, called Sourcing, Production and Logistics (SPL). (Thorvik et al., 2017)

As mentioned before, this masters thesis discusses protocols in the professional building market. Glamox's PBS division has about 60 % market share in Norway (Project Thesis, Interview, Anonymous (Person A and B), 2017). They also have strong positions in

Sweden and Finland (Volpe, 2017). The construction industry can be divided into three types, differing between the types of buildings: new buildings, renovation projects and the retrofit market. According to the Division Manager of Glamox's PBS division, there is a 50/50 distribution between the general market for new buildings and renovation projects. The retrofit market also got a market share, but currently at a negligible quantity. The number of projects going to the retrofit market is however expected to increase in the next few years (due to buildings that have transferred to LED, (which has a lifetime of 25-30 years) and the retrofitting of these lighting systems) but there has not been possible to find any predicted quantified values.

4.2 Current LMS

In the late 2017/beginning of 2018, Glamox started providing various LMSs to their customers. Currently, Glamox provides four different LMSs, each of them using different protocols (DALI, KNX, RF combined with Bluetooth and TCP/IP and combinations of these). "Glamox Wireless" is one of the LMS types Glamox provides. The British company LiteIP supplies the software and the connectivity components of the Glamox Wireless system. Glamox Wireless uses RF transmission on the 868 MHz band to send data to a Bluetooth hub which again sends data to a Samsung Galaxy Tablet. The RF transmission uses a proprietary protocol developed by the software supplier. The user of the system must have an "RF to Bluetooth Gateway" in a proper (near) distance from the Samsung Galaxy Tablet in order to control the luminaires from the tablet. Glamox Wireless can also be delivered with internet connectivity where an additional gateway (RF to TCP/IP) is a part of the system. The luminaires are controlled by the wired DALI protocol, and the RF protocol sends commands for DALI to execute. The Bluetooth and TCP/IP protocols make the GUI available through the API and the building responsible or user can control the luminaires through the tablet (or through a computer if TCP/IP is used). Appendix D presents the marketing brochure of the Glamox Wireless system and gives more details about the system architecture and component choices. (Conversations, Various Glamox Employees, 2018)

Glamox Wireless uses three or four different communication protocols, DALI, RF and Bluetooth and TCP/IP if requested. All the protocols are used to control the field devices - the luminaires. The DALI and the RF protocol is operating at the field level while the Bluetooth and the TCP/IP protocol is operating at the automation and management level - but only managing the lighting. If one wants to connect Glamox Wireless to a central BMS one would most likely use the TCP/IP solution of Glamox Wireless. The RF to TCP/IP gateway would possibly need some modification to be connected to the central API of the BMS.

With their various LMS solutions, Glamox takes on some operational responsibility for the lighting installation. Their LMS business model is similar to the business model of traditional luminaries, with a one-time purchase cost for the customer of Glamox. The new responsibility on Glamox's part is that they are responsible for the software of the LMS and must give software-support to their customers when needed. Glamox also offers commissioning of the system. All these extra services come on top of the given warranty of the luminaires. Glamox LMSs currently provides energy monitoring and there are no sensitive data issues at present. The data is owned by the software provider and Glamox has access to energy monitoring data. The next natural step for Glamox will be to collect and analyze data on the performance of the different components of the system in order to make predictive maintenance possible. (Conversations, Various Glamox Employees, 2018)

The fact that Glamox has decided to provide four different categories of LMSs, each of them relying on different combinations of communication protocols, makes the origin of writing this thesis evident. Providing commissioning and support to a system that uses up till four different communication protocols at the same time is clearly not the most straightforward solution and the various analyzes executed in the subsequent chapters of this thesis and the combination of these, will hopefully lead Glamox and the professional building industry as a whole toward more consistent use of communication protocols.

4.3 Competitive Landscape

The project thesis written as a pre-study for this thesis found that the largest barrier to IoT implementation in the professional lighting industry is the lack of common standardization. “When the use of proprietary standards, expensive licensing agreements etc. is over, there is true potential to connect lighting, heating, ventilation, security systems, mobiles, potentially everything, to the same platform. This would enable a user-friendly interface in which many customers are going to be willing to pay for” (Nerland, 2017, Project Thesis, p. 82). The main theme of this masters thesis is spot on the quote above and this sub-chapter will investigate the competitive landscape we see now. Firstly, the stakeholders of Glamox in a smart building will be investigated followed by an evaluation of Porter’s five forces.

4.3.1 Stakeholders to Glamox AS in a Smart Building

Table 4.1 on the next page, displays the most important stakeholders to Glamox AS in a typical building with smart features. Since the general knowledge of the researcher was the most important in the construction of the table, the table does not have any particular references. Stakeholders can be defined as “individuals, groups, and other organizations who have an interest in the actions of an organization and who have the ability to influence it” (Savage et al., 1991, p. 61). The table expresses that Glamox has to monitor a large number of stakeholders and holds a total of 14 categories of stakeholders, each of them representing a group of several individuals/enterprises. It has to be emphasized that the table holds the stakeholders that are most important for the scope of this thesis and that there exist other stakeholders in addition to the ones expressed in the table. There is also important to acknowledge that the expectations and requirements of the different stakeholders are diverse. The table is complete on its own and will not be explained any further.

Table 4.1: Stakeholders to Glamox AS in a typical building

<table>
<tr><th colspan="2">Stakeholders</th></tr>
<tr><td rowspan="6">Users of the building</td><td>Office workers</td></tr>
<tr><td>Schoolchildren</td></tr>
<tr><td>Cleaning personnel</td></tr>
<tr><td>Cantina personnel</td></tr>
<tr><td>Hospital patients</td></tr>
<tr><td>etc.</td></tr>
<tr><td rowspan="8">Technical building system companies</td><td>Lighting system (Glamox)</td></tr>
<tr><td>HVAC</td></tr>
<tr><td>Security system</td></tr>
<tr><td>Lift system</td></tr>
<tr><td>Fire system</td></tr>
<tr><td>Water system</td></tr>
<tr><td>Window shield system</td></tr>
<tr><td>etc.</td></tr>
<tr><td rowspan="4">Suppliers</td><td>Hardware suppliers</td></tr>
<tr><td>Software suppliers</td></tr>
<tr><td>Analytic suppliers</td></tr>
<tr><td>etc.</td></tr>
<tr><td rowspan="3">Standardization organizations</td><td>Standard Norge</td></tr>
<tr><td>ISO</td></tr>
<tr><td>etc.</td></tr>
<tr><td colspan="2">Electrical installation companies</td></tr>
<tr><td colspan="2">Technical installation companies</td></tr>
<tr><td colspan="2">Authorities</td></tr>
<tr><td colspan="2">Contractors</td></tr>
<tr><td colspan="2">Building owner/responsible</td></tr>
<tr><td colspan="2">Consultant companies</td></tr>
<tr><td colspan="2">Competitors</td></tr>
<tr><td colspan="2">Shareholders</td></tr>
<tr><td colspan="2">Society</td></tr>
<tr><td colspan="2">Employees</td></tr>
</table>

There are several ways of classifying stakeholders. One of the most common is the Savage model which classifies each stakeholder into one of four categories, according to the stakeholder's potential to impact and cooperate with the organization. According to Andersen and Fagerhaug (2001), the outcome of a stakeholder analysis should be to identify the most important stakeholders through analyzing their expectations and ability to impact the company. The matrix in Figure 4.1 on the next page shows the Savage matrix for the stakeholders of Glamox.

From Figure 4.1 one can see that Glamox has seven stakeholders in the "mixed blessing" category. These stakeholders are the most important stakeholders to monitor. The name of the category stems from the fact that these stakeholders have high potential to impact the organization and a transfer towards less cooperation turns these stakeholders into "non-supportive" stakeholders. The most dangerous stakeholders in the mixed blessing category on this behalf were found to be the suppliers (can turn up their prices or change contract agreements etc.), the standardization organizations (can settle for a protocol that is not in Glamox's interest), the contractors (can choose to cooperate with other LMS providers) and the shareholders (can vote against important LMS decisions or stop the development using other measures).

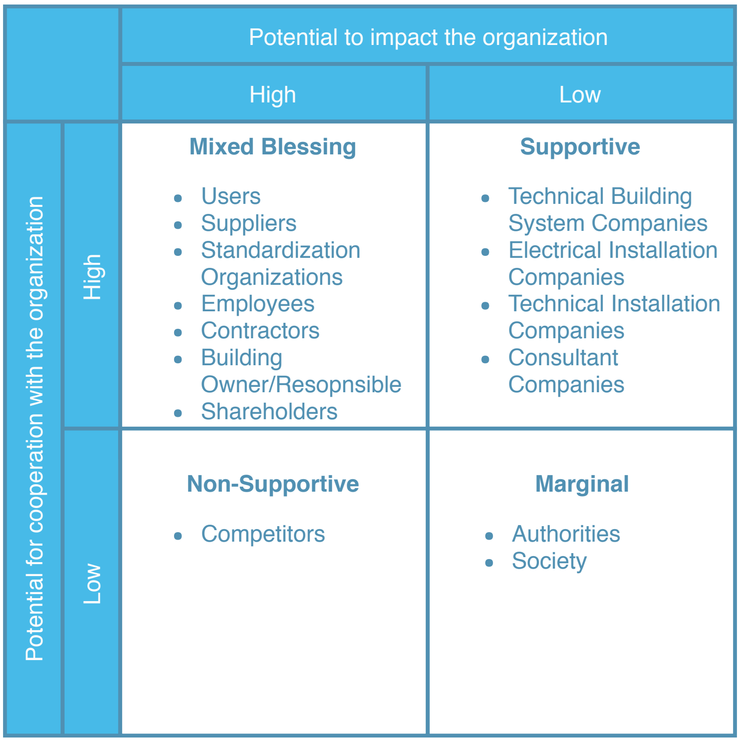

Figure 4.1: Stakeholder classification

There is important to remember that this is a picture taken of a specific moment in time. The position of the stakeholders can change rapidly and the stakeholders can transfer up, down or diagonally in the Savage matrix. In this regard, the impact of the authorities should also be commented. At present, the authorities have not influenced the LMS of Glamox to any degree. But they might introduce additional restrictions to energy usage in professional buildings - which again can lead to them providing monetary support for developing energy efficient systems as for instance LMSs. If this happens, the authorities are likely to transfer to be a supportive stakeholder.

4.3.2 Porter's Five Forces

Porter's five forces are a suited tool to analyze the competitive landscape for a given industry/enterprise. The characteristics of the five forces and the method used to construct this model were described in the methodology chapter previously (Sub-Chapter 2.3.1). Figure 4.2, on the next page, illustrates the competitive landscape for the LMS segment of Glamox as of April 2018. Since it is mainly the "Glamox Wireless" LMS that has been delivered up till now, it is this LMS that is used as reference in the construction of Figure 4.2. The report written by Porter and Heppelmann (2014), the general impression from the Frankfurt trade fair and the many conversations with different Glamox employees have been important contributions when constructing this model. In the next sections, the five forces will be described and their aggregated sum will be stated. The figure will use the following symbols to express the power of the forces: **+**: A force that is moderately in Glamox's favour. **++**: A force that is strongly in Glamox's favour. **-**: A force that is moderately against Glamox. **- -**: A force that is strongly against Glamox. **0**: Neutral force.

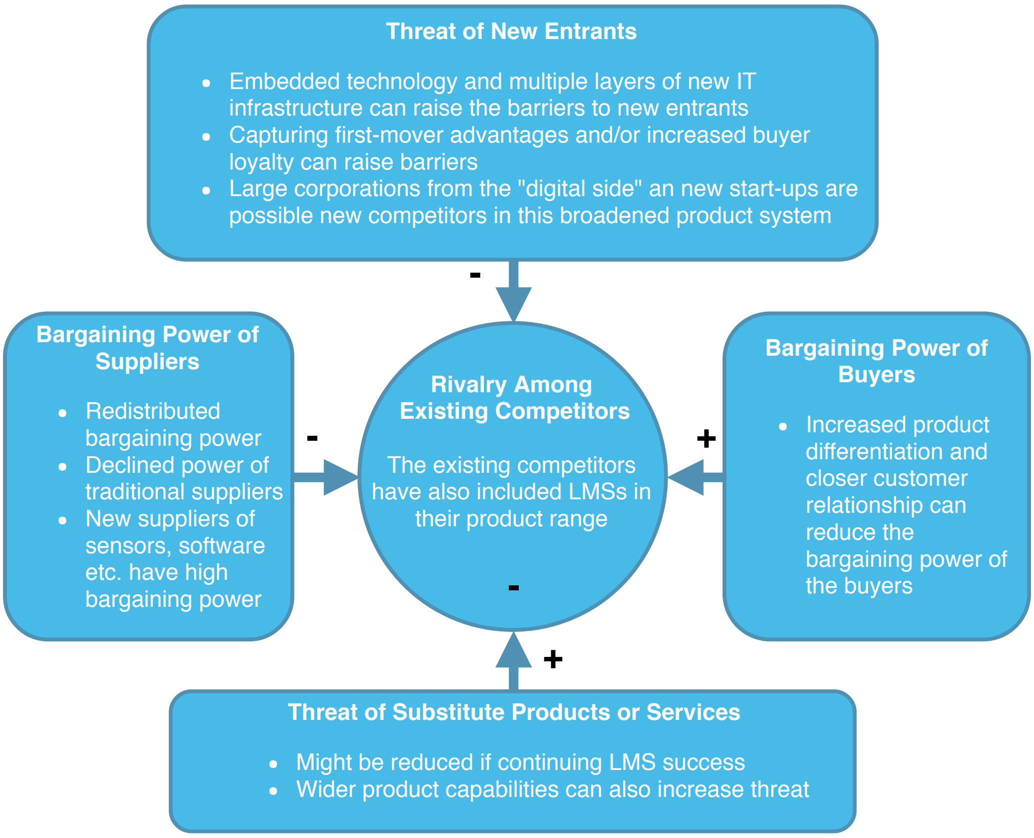

Figure 4.2: Porters five competitive forces that shape strategy for Glamox AS

The *Threat of New Entrants*-force was a bit complex to analyze since the LMS changes the possible competitors of Glamox and since it is not clear what kind of threat the large influential enterprises will pose. The LMS uses embedded technology and multiple layers of new IT infrastructure, which broadens the product definition (Glamox in not just selling luminaires anymore) and makes the product more complex in terms of software. This can raise the barriers to new entrants. Glamox Wireless has already been delivered to several projects and has gained increased popularity since its launch in January. According to Porter and Heppelmann (2014) capturing critical first-mover advantages by collecting and accumulating product data and using it to improve products and services and to redefine aftersale service can raise barriers to new entrants. The new products can also increase buyer loyalty and switching costs, further raising barriers to entry (Porter and Heppelmann, 2014). Glamox Wireless might capture some first-mover advantages in the European market, and especially in Norway. There are also reasons to believe that Glamox Wireless will increase buyer loyalty and switching costs.

There are however several reasons for believing that this force will be in disfavour of Glamox. Large corporations from the "digital side" are possible new competitors in this broadened product system. This type of new entrants is probably one of the most difficult aspects to assess in this new smart environment. Possible new entrants are Apple, Google and Amazon, which all can turn the whole industry up-side-down like Uber has done with taxis and Airbnb with hotels. One can claim that these corporations got the worlds best IT competence and a solid financial and technological platform. If one or more of these enterprises enter the professional building market, the traditional players will be strongly affected. According to Volpe (2017) the number of "Traditional" players face an increasing number of start-ups (Gooee and Casambi, to mention some). There were numerous of such enterprises at the trade fair in Frankfurt who possibly could pose a threat to Glamox. BIS Research (2017) discusses this force in detail in their report and stated that the overall threat of new entrants for the established players is high in the intelligent lighting market. “Since smart market lighting controls are manufactured in volumes, the economies of scale would vary largely for new entrants, as compared to existing players, thence making the threat of new entrants low for the existing players. However, the ease of availability of raw materials to the new entrants establishes high degree of threat of the established players. Since the components used in smart lighting manufacturing are common electronics products, the manufacturer can switch to make other products, such as smart agricultural products and others. Thus, this is making it easy for the intelligent lighting control manufacturers to exit from the market, and lowering the exit barrier. This, in turn, results in the increasing threat of new entrants for the established players” (BIS Research, 2017, p. 64).

Combining the factors in favour of Glamox and the factors in disfavour of Glamox, this force is expected to be moderately against Glamox. Since the global intelligent lighting control market is estimated to witness a growth at a CAGR of 13.3 % and 20.9 % over the period 2018 to 2024 in terms of volume and value respectively, there is seen to be an increased threat of new entrants (BIS Research, 2018). There is also worth mentioning that the last bullet point from the box in Figure 4.2 make a strong argument for setting this force to being strongly against Glamox as well, but there is not found any signals for such a transition and this factor is thus not seen as the main case at present. This aspect emphasizes the importance of continuously monitoring the forces.

The *Bargaining Power of Suppliers*-force is an important force to evaluate for Glamox. The LMS needs electrical components as relays, controllable breakers, actuators, transmitters and receivers as well as sensors, gateways and similar (BIS Research, 2017). These components are common and are used in various other electronic products and industries. Hence, there are various substitute buyers to purchase these components, resulting in the high bargaining power of suppliers. Glamox must also allocate suppliers that can provide the needed software and analytic capabilities (if they choose to outsource such functions). These suppliers will also have high bargaining power. Their current partnerships with LiteIP and Prolojik (provides the central monitoring features) has shown that it is possible to have a good dialogue with such suppliers. The traditional suppliers will continue to be important since the LMS will still need quality lighting, but their total bargaining power will decline as the bargaining power will be distributed among several other actors. Because of the new suppliers of electrical hardware, software and data analytics, the total strength of this force will most likely result in a force that is moderately against Glamox.

Bargaining Power of Buyers is also a force with several contradicting factors. According to BIS Research (2017) the overall bargaining power of buyers in the intelligent lighting control market us low. With their LMS, Glamox has gained increased product differentiation which reduces the bargaining power of the buyers. As stated in Porter and Heppelmann (2014), access to product usage data or providing a business model which reduce the cost of switching to a new service provider increases the buyer power. With Glamox Wireless, the business model is as with traditional luminaires and there is currently no sensitive data at stake (only energy monitoring). As Glamox Wireless evolves there will probably be a need to change the business model as the amount of data collection increases which can increase the buyer power. This force is sat to be moderately in Glamox's favour because the current product they are offering seems to limit the influence of the possible factors that can increase the buyer power.

The *Threat of Substitute Products or Services*-force is hard to assess at this point, but one thing is certain: Buildings will need artificial light. The question here regards the value-added services. Services such as analyzing room usage parameters can be inherent in other products and such products could possibly be a threat. Glamox Wireless currently has one value-added service, energy monitoring of the luminaires, which has very few or none substitute products or services. Therefore, this force is sat to being moderately in Glamox's favour. In their expansion of their LMSs, Glamox should be careful to implement value-added services that do not increase the overall value of their product, since this has the potential to increase the strength of this force and make it in disfavour of Glamox.

Rivalry Among Existing Competitors. According to BIS Research (2017) the overall intensity of competition in the intelligent lighting controls market is high. This is because there is a high number of competitors which is expected to make new investments in the IoT field. Most of the actors operate globally which diversifies the competitive scenario and further increases the intensity of competition (BIS Research, 2017). This force puts a pressure on Glamox at present and is expected to increase as the competitors implement additional IoT functionalities in their products. As previously stated, the LMS will have to interoperate with the central BMS and the enterprises with the capabilities to take a strong position in the digital building platform will be the winners. This force is thus set to being in moderate disfavour of Glamox.

There is a large number of contradicting factors in this model and it is very hard to come up with a final, explicit answer. When summarizing the pluses and minuses in the figure we get a total of (-). From this, it can be concluded that the competitive landscape for Glamox in the IoT environment in the PBS sector is moderately in Glamox's disfavour. The main reason for this is found to be the bargaining power of the suppliers, the threat of new entrants and the rivalry among the existing competitors. Having a total pressure that is moderately in disfavour is not necessarily a bad thing for Glamox and they can, of course, make revenue, expand their customer portfolio and develop new bestsellers in this competitive landscape. There is also important to emphasize, again, that this is a highly evolving landscape with no clear future and it is important for Glamox to continuously monitor these five forces.

In this chapter, Glamox has been introduced and analyzed in a general way. In the next chapter, the analysis will take place. Here we will go back to the communication protocols and use different analyzes to find the most probable protocols at the different levels of building management.

Chapter 5

Analysis

This chapter is probably the most important chapter of this thesis and one can say that the previous chapters have been building up to this. The analysis is divided into five parts. Firstly, important considerations in the choice of protocol will be analyzed with the aim to find the most important success factors. Secondly, the questionnaire will be analyzed and its results interpreted. Sub-Chapter 5.3 performs a simplified CBA, comparing the two most likely protocols at the field level according to the questionnaire results. In Sub-Chapter 5.4 an MCA based on the success factors and the questionnaire results will be presented. Lastly, in Sub-Chapter 5.5 the three methods used to analyze the future protocol usage will be compared. This chapter will aim to answer SQ (d), (e), (f) and (g).

5.1 Important Considerations

This sub-chapter will first take the discussion about wireless vs. wired protocols and analyze the evidence found in the literature. After this, the IP protocol will be discussed along with a comment on edge computing. Lastly, in Sub-Chapter 5.1.3 the most important success factors for Glamox AS will be presented.

5.1.1 The Wired vs. Wireless Discussion

According to BIS Research (2017) the global intelligent lighting controls market is categorically segmented into wired and wireless technology, on the basis of connection type. In 2016 the wired connection type held a higher market share in terms of value, of 53 %. BIS Research (2017) further stated that wired technology has been more prevalent but emphasizes that with the recent development of RF technologies, there is an increase in the number of wireless installations worldwide. (BIS Research, 2017)

There is a lot of discussion regarding the use of wired vs. wireless protocols and as stated by BIS Research (2017), it depends on the user's requirements to prefer any of them. The most clear benefit of using wireless technology is that it provides flexibility in terms of installations and for wired technology, the most clear benefit is the high reliability. In Table 5.1 on the next page, the main advantages and disadvantages of wired and wireless protocols are presented. For simplicity, superscript referencing is used. The superscripts means the following references: 1 = BIS Research (2017); 2 = Schneider Electric (2015); 3 = Curran (2014). The table is complete on its own and will not be explained any further.

Table 5.1: Comparison of wired and wireless protocols

	Wired	Wireless
Advantages	Suited for new construction where running wires is not a significant extra expense[2]	Low installation cost compared to wired [3]
	High performance and reliability [2] - hard wiring of system eliminates the potential for communication issues due to interference or signal propagation limitations[3]	Flexibility – the lack of in-wall wiring allows greater flexibility in changing control configurations in the future [3]. Scalability through easy addition of devices [2]
	High security – ability to gain unauthorized access to hard wired control systems is more difficult (although not impossible)[3]	Suited for retrofit applications [3]
	Fault detection – hard wiring allows easier troubleshooting using equipment such as time domain reflectometer tools which can pinpoint the location of faults along wire runs[3]	Less planning – since there are no in-wall requirements, advanced planning for controls is minimized[3]
Disadvantages	Must lay up the wires	Reduced performance when bad weather conditions [1]
	Maintenance, change of wire, updates, etc. may be difficult	Can have low reliability. Mesh networks uses time to stabilize after being off line
		Range limitations and inference with other devices [1]

Wang (2010) discusses the application of wireless technologies in BMSs at the field, automation and management level respectively. At the field level, wireless sensor networks using RF technologies is well suited. The usually low bandwidth with RF technology is sufficient for the relatively low data rates that we find in sensor networks. Power is supplied to the sensors by batteries, so low power usage is desired and devices that go to sleep or similar is thus preferred. The power of actuators is not an issue as it is usually supplied by Alternating Current (AC) line power. The automation level needs wider bandwidth since it transmits more data than a wireless sensor network and thus likely requires a higher frequency band to support higher data rates. The controllers at this level are usually installed where AC line power is available, so the power supply is not an issue for the application at this level. The management level involves computers, network controllers, or other Ethernet-ready devices. Due to its high traffic and TCP/IP compatibility, the Wi-Fi standard can be implemented to establish a wireless connection of an Ethernet-ready field panel to a facility's existing wired or wireless LAN. (Wang, 2010)

Wired and wireless protocols have many differences and are suited for different applications. There is crystal clear that the wiring procedure needed with wired protocols needs electricians with correct competence and material for both the actual wires and for the mounting tools. Wireless protocols are a lot more flexible and can often be mounted by anyone. When it comes to reliability, wired protocols is superior at present. Wireless signals can interfere with each other and in the worst case be totally blocked (See for instance: Kringenberg (2018)). The general trend in the technological environment at present is a transfer towards more wireless technologies. According to Simon Slupik, CTO of Silvair and chair member of the Bluetooth Mesh group, the wired vs. wireless debate is over now. “Nobody asks us to justify mobile phones, for instance. Wireless wins because of its flexibility and the cost advantage is huge” (Molony, 2018). As the CTO of Silvair (which have developed a protocol for lighting control based on Bluetooth Mesh), Slupik has personal incentives in stating this, and his opinion must be evaluated with caution. However, written evidence of the advantages he mentions has been found in many articles throughout this writing period and there is therefore seen to be some truth in his statement.

The three categories of professional buildings, new buildings, renovation projects and retrofit projects (existing buildings) got differing characteristics and features. The wired protocols are best suited for new buildings and renovation projects (but is not an optimal solution since the demands to the BMS will most likely change during the lifetime of the building and the wired protocols make up/down-sizing etc. difficult). The retrofit market has as mentioned, a negligible market share, but is expected to increase in the next years. The wireless protocols are, as stated in the table, suited for retrofit applications. If we look at the 2-5 year time frame of this thesis, there is not expected to be any large change in the market shares of the three types of buildings, but there is expected to be a change in demands to functionality, flexibility and management functions of the BMS which again gives the wireless protocols an advantage.

5.1.2 The Internet Discussion

Is the IoT synonymous with the Internet you may ask. Not necessarily is the answer. Although all the protocols discussed in this thesis can be connected to the Internet through the use of gateways, the protocols do not connect to the Internet itself. In order to do so, one needs to use the Internet protocol suite in all the networks in building management (field, automation and management network). If one does so, one gets “IP to the Edge”. This concept is discussed by Rowland et al. (2015). They stated that many edge devices cannot speak or understand internet communications without translation by a gateway and that there is not yet a standard way to translate between internet networking (TCP/IP) and most non-IP network protocols such as Bluetooth or ZigBee. They further discussed that this limits the edge devices to doing only what the gateway apps allow since the Internet service can not talk directly to the edge devices and ask them anything else. “Delivering Internet communications (over IP) all the way to the edge device, across even low-powered networks, is a growing area of interest, to provide many more edge devices with a unique identity on the Internet so they are able to contact (and be contacted by) any service and do anything they want. This is a true Internet of Things” (Rowland et al., 2015, p. 85). (Rowland et al., 2015)

Transferring to the true IoT would enable a far greater degree of flexibility of functionality. “Instead of asking the gateway to pass on a message to a device and hoping that the gateway knows what to do with your particular request, you can contact it directly. You could compare this to the convenience of having a person’s mobile number, as opposed to an office switchboard where you need to leave a message with a receptionist. If you have the mobile number, you don't need to know where they work in order to get hold of them" (Rowland et al., 2015, p. 85).

Each "Thing" on the Internet needs a unique IP address. In order to have enough addresses, a new IP standard is under development/adaption. With the current IPv4 standard there exist 4 billion possible IPv4 addresses, which may seem like a lot. But it is not enough to support the billions of connected devices predicted to come online in the next few years. The new IPv6 standard provides for the equivalent of 10 IP addresses for every atom on earth - which clearly will be sufficient for the foreseeable future. (Rowland et al., 2015)

But how should the IP be implemented to the edge when the wireless technology used at the physical layer - Wi-Fi - is clearly not a good option? According to Rowland et al. (2015) there are initiatives in the development that would allow IP networking to run on top of Bluetooth, ZigBee, and other low-powered local area protocols. As mentioned in Sub-Chapter 3.3.8 about the Internet protocol suite, the combination of the IEEE 802.15.4 protocol and the 6LoWPAN protocol makes low-power personal area networks possible. The greatest benefit in getting IP to the edge is that one can use the same application protocol to talk to all the devices without thinking about how the devices connect at the link layer or translate between different network protocols. As engineer and founder of 1248.io, Pilgrim Bart puts it: "Using the Internet (even to go a few meters from your smartphone to e.g. a PVR [Personal Video Recorder] or audio system) may sound technically rather mad, but it has the huge benefit that it avoids the problem of physical standards, using the Internet as a lingua franca. Your phone and the PVR may not support the same physical standards but they can still communicate. It also allows you to remote-control from anywhere in the world" (Rowland et al., 2015, p. 86).

The required standards and application protocols for making IP to the edge are not yet launched and there is also worth mentioning that making connected devices directly reachable on the Internet opens up security risks that would have to be mitigated (Rowland et al., 2015). However, IP to the edge has a great potential and seems to be the only way of getting one protocol in all the layers of BMS. Much is not yet in place and there are several issues that have to be solved before this could become a reality. There are exciting times ahead of us, and individuals and enterprises involved in the IoT and BMS environment should definitely monitor the future Internet protocol suite.

5.1.3 Success Factors

In this sub-chapter, the success factors regarding the choice of protocol in BMSs will be given. Each section will present a success factor in italic and elaborate the given success factor. The paper of Arrow Electronics Inc. (2016) has been the most important in finding inspiration regarding what is the most important success factors. The main consideration Glamox has to take regarding each success factor will also be given.

The protocol should be suitable for the size of the installation (Arrow Electronics Inc., 2016). This factor regards how many end-points must be connected and the requirement for central control. Arrow Electronics Inc. (2016) writes that for large installations, wired protocols can greatly increase the complexity of the network and the cost of wiring and installation. Glamox delivers LMSs to a wide range of projects and since it is desirable to find one protocol that is suited for all applications, Glamox must seek for a protocol that fits this variation in both size and technical requirements.

The protocol should provide scalability of the network (Arrow Electronics Inc., 2016). This is a key success factor in the rapidly evolving IoT world and choosing a protocol that provides the capability for future enhancements is a key. Glamox should consider the protocols that easily allow adding or removing lights from the network. The demand for up or downsizing of the system depends on the building type, but most professional buildings can be sold or change user requirements during the (long) lifetime of an LMS using LED technology. Open office spaces are one obvious example of a room that needs to be flexible. There are also reasons to believe that the users of the buildings will pose an increasing demand of flexibility of their light system due to the fact that more of them will have such features in their (smart) homes. Glamox must continuously monitor their customers' demands and make sure that the communication protocols can handle the future enhancements.

The protocol should have the capability to interoperate with other devices and systems (Arrow Electronics Inc., 2016). There is important to choose a protocol that has the capability to interoperate with other devices and systems. Reasons for this are described in detail in Sub-Chapter 3.2.4. In the smart building context, many building integrators want one functioning system instead of many small specified systems, even though the specified systems can have more functions. There is also important to make sure that the protocol can handle the possible future upgrades of the other protocols in the system. For Glamox it is important to keep an eye on the other companies providing technical installations to the professional buildings and to choose a protocol that interoperates with their protocols.

The protocol should have sufficient range of communication (Arrow Electronics Inc., 2016). The protocol must have a sufficient range that fits with the building application. For the wireless protocols considerations related to environmental losses (noise, interference, obstacles such as walls or barriers) should be taken. There is also important to remember that the protocols often have other restrictions in addition to the range as the permitted number of nodes per gateway/hub/router etc. For Glamox the range requirements will vary among the different building projects, but a maximum range of about 30 meters between two network nodes for a given protocol should be sufficient for most buildings.

The protocol should be reliable, fast enough and have minimal latency. A BMS must be reliable as an offline BMS can give serious consequences. What happens if the security alarm, the emergency light system or the elevator has a malfunction? The consequences could in the worst case be fatal. A malfunction of the general artificial light system will probably not be that serious but it can lead to for instance loss of working hours in an office building that could lead to poor performance of the given enterprise. It could also lead to serious irritation and a spin-off effect. This was emphasized by the Sales Director LMS during the semi-structured interview. The user demands that the luminaire/luminaires enlightens instantly after the given "on" command is executed. If the command is given through pushing a button, and the luminaire/luminaires does not enlighten right away, the user will continue to push the button and the whole system could possibly crash. An LMS with a second latency is a poor LMS. According to Rowland et al. (2015), less than 0.1 seconds of latency is not noticed by the user. 0.2-1.0 seconds of latency will be noticed but the user thinks the computer is working on the problem and a latency of over 1.0 seconds is definitely noticed and the user will expect some kind of feedback (Rowland et al., 2015). The bandwidth must support the amount of data transferred per time unit but it is hard to set a specific number. A bandwidth over 100 kbit/s is sufficient at the field level for lighting at present but if one for instance want to monitor and analyze a high resolution surveillance video system this bandwidth is not sufficient.

The protocol should be secure (Arrow Electronics Inc., 2016). According to Arrow Electronics Inc. (2016), hackers have already proved that breaching a light to gain access to the entire network is possible. The seriousness of a hacker attack will be largely affected by what kind of data is hacked but securing the network and endpoints is especially critical in today's connected environments either way. There is not anything special to comment for Glamox in this regard and they must make sure that the user data is secure and pursue the laws in force.

The protocol should have a competitive cost of installation and maintenance (Arrow Electronics Inc., 2016). As any other technology choice, the cost of investment must be affordable and competitive on the market. The total cost during the lifetime of the product should be considered. There is not anything special to comment for Glamox in this regard.

The protocol should fit device management requirements (Arrow Electronics Inc., 2016). The protocol should fit the demands of the device management. If remote control is demanded, the chosen protocol must be wireless or interoperate with a wireless protocol. Consumers continue to expect their lighting system to have more and better inherent functions, management possibilities and GUI's. Glamox must monitor these increasing requirements and try to keep up with and at best case be in front of these changing needs.

The protocol should be aligned with the industry trends (BIS Research, 2017). Industry trends are very important in the choice of protocol. Since no protocol has been said to be the "standard protocol" by now, one expert opinion can change the whole picture. The same if one large influential enterprise as Google for instance, suddenly takes a strong position in the BMS environment. Then, the chosen protocol of Google would probably soon after be seen as the industry standard. There are no special aspects to comment for Glamox in this regard and the five force analysis done in Chapter 4 has monitored the industry trends.

The nine success factors presented above, all shed light on the importance of context. The choice of protocol must fit the usage area (type of room/building), the other protocols in the system and the functions of the connected devices. For Glamox, there are reasons to believe that with a total pressure that is moderately in disfavour (Porter Model), there will not be taken any big chances when it comes to technology. Glamox would therefore prefer to go for a protocol that is mature and well accepted. The next sub-chapter will present the results of the questionnaire and give a baseline for figuring out which protocol is the most accepted at the different levels of building management.

5.2 Analysis of Questionnaire

The responses from the questionnaire were logged and analyzed in Microsoft Excel. In the following sections and figures, the most important results from the questionnaire will be explained and illustrated. Appendix C provides the graphs in full scale and Appendix E illustrates the "raw" data. In the following section, each of the questions of the questionnaire will be analyzed. The chosen analysis methods, pie and bar charts, are described in Sub-Chapter 2.3.2 in the methodology.

Figure 5.1 below, shows the results of Q1A of the questionnaire which asks about in what degree the respondents think the IoT will change the current BMSs. There were a total of 47 responses to this question. The figure shows that 23 of the respondents, almost 50 %, thought that the IoT will provide a large change on the current BMSs. There is also worth noticing that 10 of the respondents, 26 %, ticked "Total change" on this question and that a few more, 12 respondents, ticked "Some change". There was no one that ticked "No change". All of this emphasizes that there is agreement among the industry actors that building management is changing due to the IoT, and that the IoT will most likely induce a large change. The question does not ask about which kind of change the respondents think will occur, but it is assumed that the respondents think of a change towards more connectivity and digitalization because of the IoT focus of the question.

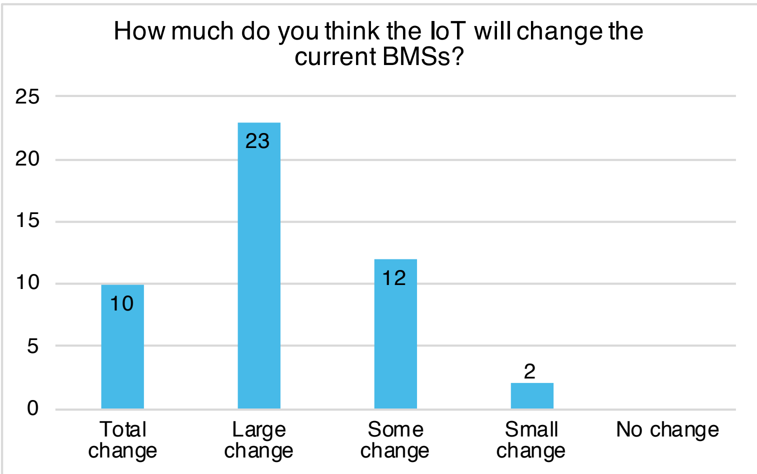

Figure 5.1: Bar chart of Q1A responses

The second question on the questionnaire asks about in which degree the respondent agrees with the statement "There are often numerous different communication protocols operating at the same time in a BMS in a professional building". Figure 5.2 on the next page, illustrates that the result of this question is without doubt. 30 of the respondents, 65 %, agrees (and 11 of the respondents, 24 %, strongly agrees).

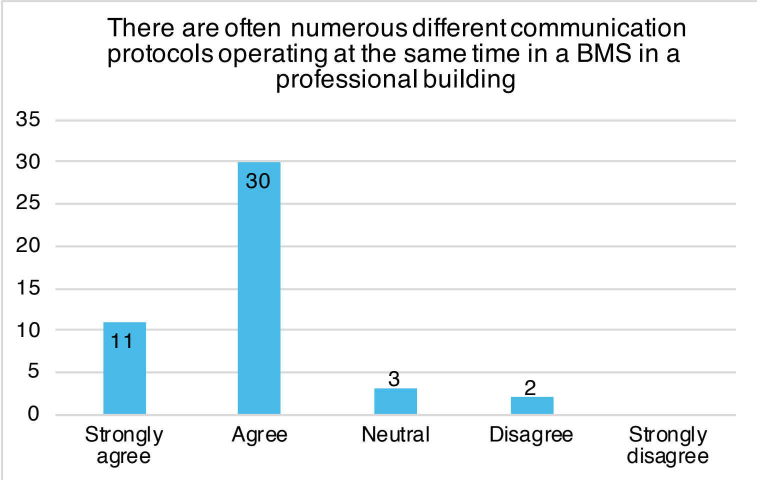

Figure 5.2: Bar chart of Q1B responses

Q1C on the questionnaire also got a strong conclusion as can be seen from Figure 5.3 below. 27 of the respondents, close to 60 %, agrees that it is often hard to achieve interoperability between the different protocols in BMSs. This aligns well with the theoretical discussion about interoperability in Sub-Chapter 3.2.4

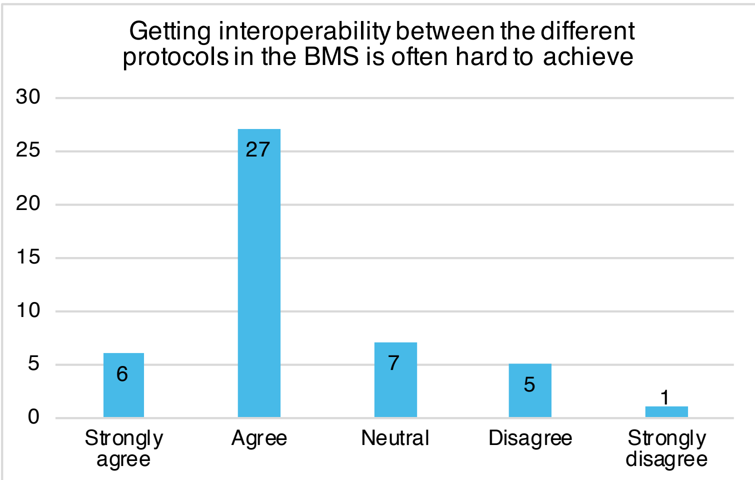

Figure 5.3: Bar chart of Q1C responses

Question 2 on the questionnaire is the main question and the responses to this question will be an important contributor to the final answer of the RQ of this thesis. Figure 5.4 on the next page shows a bar chart of all the responses to this question.

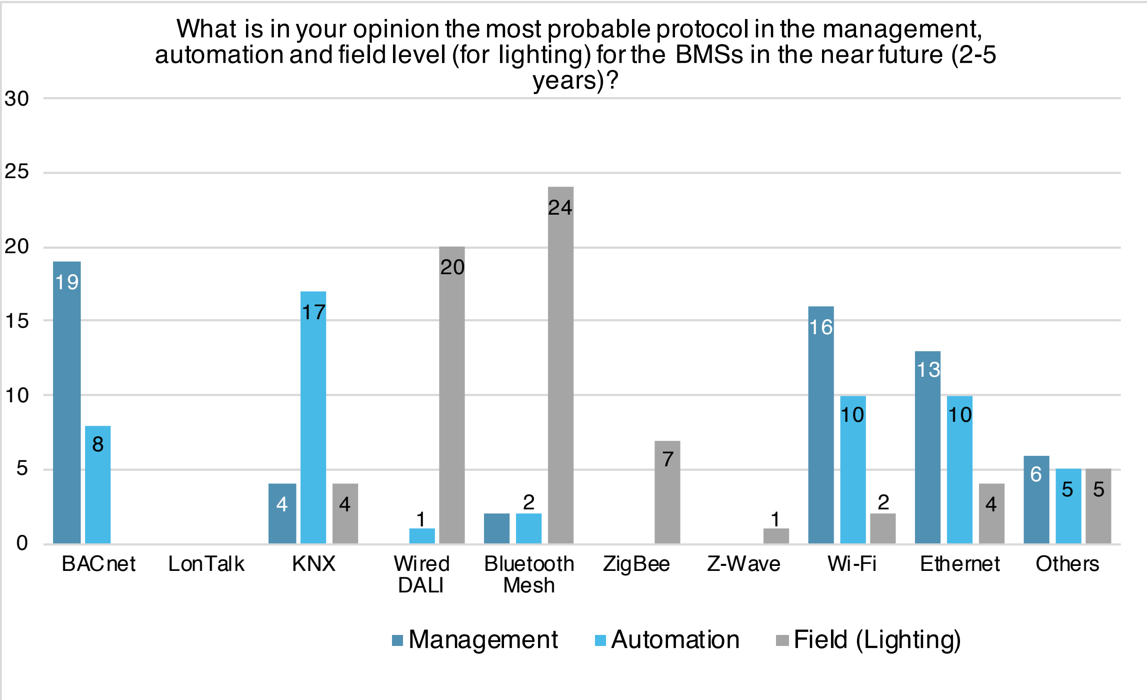

Figure 5.4: Bar chart of Q2 responses

There is of course of large interest to go a bit further into the results of this question. Figure C.5, C.6 and C.7 in Appendix C shows the full pie charts of the results and Figure 5.5 below gives the most important values from these pie charts.

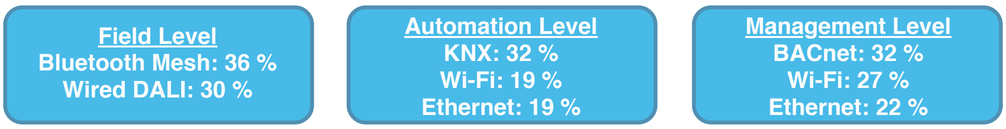

Figure 5.5: Main results of Q2 in percent values

As can be seen from the summary-figure above, the most likely protocols at the three levels of building management are Bluetooth Mesh for lighting at the field level, KNX at the automation level and BACnet at the management level. This combination of protocols will be named Scenario 1 in the following sections. The second most likely protocols at the three levels are DALI, Wi-Fi/Ethernet and Wi-Fi. This will be named Scenario 2. A third option, which in fact is more likely than Scenario 2 is to have Bluetooth Mesh, Wi-Fi and Wi-Fi. This is a totally wireless scenario and will be named Scenario 3. Appendix F holds three figures which illustrate the architecture of these scenarios. The protocols operating at the other field level systems is outside the scope of this thesis and is not described.

The Arrow Electronics Inc. (2016) report, comments a market research performed by Strategies Unlimited. This research found that DALI was the most used protocol for lighting applications in North America in 2016 with a usage rate of 32 %. Hybrid protocol solutions (combining two or more protocols) got a usage rate of 29 % and the Bluetooth protocol (Bluetooth LE/4.0) had only a 4 % usage rate. Arrow Electronics Inc. (2016) also reports predictions about protocol usage in different industries in North America in the next 3-5 years (ranging from 2018-2020). From their figures, one can see that Wi-Fi will be a strong leader in the retail and office sector followed by Bluetooth and ZigBee. For the industrial sector, powerline communication is predicted to be most common followed by Wi-Fi. The hospitality segment has somewhat the same predictions as the retail and office sector with Wi-Fi on top followed by Bluetooth and ZigBee. But for the hospitality sector wired protocols as powerline and DALI also got a noticeable share. The numbers presented by Arrow does somehow align with the results on Q2 on the questionnaire and one can thus suggest that there are similarities between North America and Europe. There is though no doubt that Wi-Fi has not gotten the predicted market share of Strategies Unlimited in Europe.

An article written on the Lux Review web page writes the following in their predictions of the 10 big lighting trends of 2018: “Bluetooth will win the protocol war” (Lux Review, 2018). This prediction is equal to the questionnaire result of the lighting predictions (field level for lighting). The 4 % prediction from 2016 made by Strategies Unlimited does however not comply with this. This emphasizes the many different opinions in this field and that the year-to-year predictions are widely varying.

Figure 5.6 below, illustrates the working title of the respondents. As discussed in the methodology, many of the respondents seemed to overlook this question and did not write their current working title on the questionnaire. There is therefore made an N/A (not answered) category in the bar chart. The categories expressed in the bar chart is constructed by the researcher when analyzing the responses. As can be seen, there were mostly engineers/technicians among the respondents, followed by marketing/sales personnel, product managers and general managers/CEO.

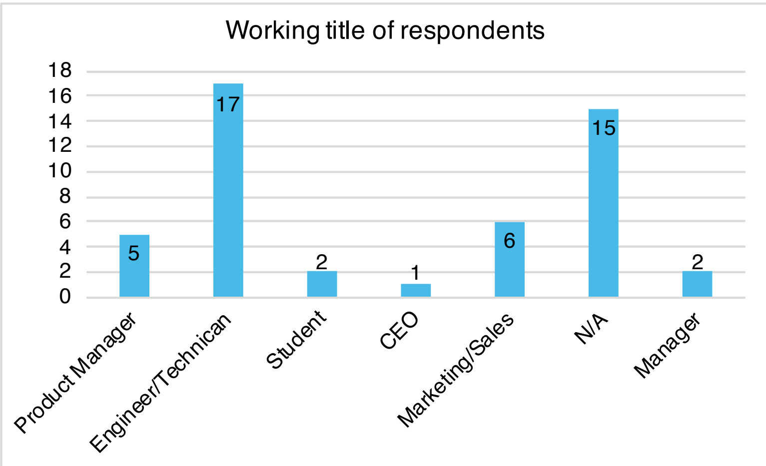

Figure 5.6: Bar chart of Q3 responses

Other important takeaways from the questionnaire are the following: (1) There were only two women among the respondents. This reflects that the exhibitors at the Light + Building trade fair are mostly men and that building and light management in general is a male-dominated industry. (2) Only one respondent ticked “TCP/IP Ethernet” on all the BMS levels. This reflects that “Power over Ethernet” (related to IP to the edge, discussed previously in Sub-Chapter 5.1.2) which has been promoted by many enterprises and scholars in the recent years has not gotten the predicted footing. (3) Eight of the respondents did not answer all the questions. This could reflect that not all the respondents had the required knowledge to answer all the questions.

The questionnaire asked some pretty detailed technological protocol questions and found that the respondents think the Bluetooth Mesh protocol is most likely to dominate at the field level for lighting. Six percent point behind we find the protocol that is currently the most used in lighting control in professional buildings, namely the DALI protocol. Based on this, it was seen to be of high interest to dig a bit more into the differences between the costs and the benefits of these two protocols. This was done through a simplified CBA and will be described in the next sub-chapter.

5.3 Simplified Cost-Benefit Analysis

The methodology behind this analysis was described in Sub-Chapter 2.3.3 and the full analysis can be found in Appendix H. The current LMS of Glamox uses the Bluetooth protocol for managing the luminaires but is dependent on the DALI protocol for performing the commands. Transferring to only using Bluetooth to control the lights is a possibility Glamox has considered, but reasons such as customer demands, competence within the organization, supplier agreements etc. has made Glamox to postpone this transfer. There is also important to recall that the Bluetooth Mesh topology instruction set is quite new and that many enterprises are still struggling with the implementation of this technology. Having more knowledge regarding the differences between DALI and Bluetooth when it comes to consequences (costs) and benefits (income) would make the decision making of Glamox more solid. Conducting a CBA with the aim to compare all the costs and benefits that occurs during the lifetime of the LMS was therefore of large interest.

In addition to using a non-monetary ranking scale for representing the costs and the benefits of this analysis, several other simplifications/assumptions were made. The first thing that is important to mention in this regard is that the CBA reflects the lifetime balance sheet of the LMS. Secondly, the office building described in Appendix G was used as reference. This can be seen as a limitation of the analysis since using a school or a hospital certainly would have given some other aspects to consider.

Table 5.2 on the next page shows the CBA. The CBA is constructed in a systematic manner with listing the benefits first, followed by the costs and the bottom line. The costs and the benefits are divided into two characteristics: Direct and indirect. Direct benefits are benefits that could be directly expressed with a monetary value (if such values are available) and is divided into sales income (the one-time income from the sale of the LMS) and subscription income. The indirect benefits are benefits that are not directly connected to the LMS or that is not that easily monetized. The indirect benefits are divided into the benefits from synergies to sale of other products, reduced energy usage, increased productivity, comfort and flexibility. Increased productivity and flexibility is confirmed to be benefits by BIS Research (2017) and increased flexibility is discussed in for instance Memoori (2017). The direct costs are divided into four logical segments, namely the cost of purchase/material, production, installation and operation. The indirect costs are divided into initial and ongoing training, downtime revenue loss, support cost and environmental degradation. The cost of downtime revenue loss is for instance described by Jansen (2014). The two protocols are compared from four different perspectives, Glamox, the building responsible (abbreviated BR in the table), the user and the society. The three last pages of Appendix H has an explanation of every cell in the CBA and readers who want to know the reasoning behind the numbers in the CBA are directed to these pages.

Table 5.2: Cost-Benefit Analysis

	DALI				Bluetooth Mesh			
Direct benefits	Glamox	BR	User	Society	Glamox	BR	User	Society
Sales income	5	0	0	0	7	0	0	0
Subscription income	2	11	0	0	3	13	0	0
Indirect benefits								
Synergies to sale of other products	1	0	0	0	2	0	0	0
Reduced energy usage	0	1	2	5	0	1	2	5
Increased Productivity	0	0	1	2	0	0	1	2
Increased Comfort	0	0	1	1	0	0	1	1
Increased Flexibility	0	0	0	0	0	2	1	1
Sum benefits	8	12	4	8	12	16	5	9
Direct Costs								
Purchase/Material cost	2	5	0	0	3	7	0	0
Production cost	2	0	0	0	2	0	0	0
Installation cost	0	3	0	0	0	1	0	0
Operating cost	0	1	9	0	0	1	10	0
Indirect costs								
Initial and ongoing training	1	1	0	0	2	2	0	0
Downtime revenue loss	1	1	2	2	2	2	3	3
Support cost	1	1	3	0	1	1	5	0
Environmental degradation	0	0	1	3	0	0	0	1
Sum costs	7	12	15	5	10	14	18	4
Bottom Line (Benefits-Costs)	**1**	**0**	**-11**	**3**	**2**	**2**	**-13**	**5**

As can be seen from the CBA table, the Bluetooth solution has more benefits than DALI for all the stakeholders. One can also see that the costs are generally higher with Bluetooth for Glamox, the building responsible and the user and less for the society. The bottom line is, however, also a larger quantity for Bluetooth than for DALI for most of the stakeholders. Table 5.3 below, compares the two protocols more straightforwardly. The table shows that Bluetooth is found to be more beneficial than DALI for Glamox, the building responsible and the society and less beneficial for the user.

Table 5.3: Cost-Benefit Analysis bottom line comparison

Bottom Line Result	Glamox	BR	User	Society	Total
Bluetooth	2	2	-13	5	-4
DALI	1	0	-11	3	-7
Bluetooth - DALI	**1**	**2**	**-2**	**2**	**3**

Bluetooth was found to be one unit more beneficial than DALI for Glamox. This is a small number and one can claim that the two protocols are equated. The most uncertain cells in the CBA for Glamox is the direct benefits and the purchase/material cost. Bluetooth will provide more sales and subscription income than DALI, but how much more is hard to predict. At present, Bluetooth parts are more expensive than DALI parts, but the costs of Bluetooth are predicted to decrease as the technology is more adapted. For the building responsible, Bluetooth was found to be two units more beneficial than DALI.

The main reason for this is the increased flexibility and the decrease in installation costs for Bluetooth. The most difficult posts to quantify for the building responsible was the subscription income and the gap between the incomes for DALI and Bluetooth. DALI was found to be more beneficial for the user. The main reason for this is that the Bluetooth protocol got three units more costs than DALI which stems from the higher operating cost, cost of downtime revenue loss and support cost. The general society was found to benefit the most of the Bluetooth solution. The main reason for this was the lower environmental degradation cost. The Bluetooth protocol is less material intensive than DALI and this should certainly be taken into account when solution providers are selecting between the two protocols.

The total balance-result is that the Bluetooth protocol is three units more beneficial than the DALI protocol. This is a medium-sized number in the scope-range of this CBA and there are thus reasons to claim that the Bluetooth protocol, in fact, is more beneficial than the DALI protocol. Since it was challenging to collect actual numbers of the costs and benefits of the two protocols it was of interest to compare other important factors of the protocols, using a ranking scale instead of costs/benefits measures. It was also of interest to look at the whole BMS, using the three scenarios based on the questionnaire results. This was done through an MCA and will be presented in the following sub-chapter.

5.4 Multi-Criteria Analysis

Performing an MCA looking at the success factors described in Sub-Chapter 5.1.3 and the three most likely protocol combination scenarios from the questionnaire were of great interest for getting a comparison foundation and for finding how the scenarios perform at the various areas. To recall, the three scenarios use the following protocols at the field, automation and management level respectively:

- Scenario 1: Bluetooth Mesh, KNX and BACnet
- Scenario 2: DALI, Wi-Fi or Ethernet and Wi-Fi
- Scenario 3: Bluetooth Mesh, Wi-Fi and Wi-Fi

Table 5.4 on the next page illustrates the MCA. The general methodology used in the execution of this analysis was described in Sub-Chapter 2.3.4. Using the threefold scale of 1, 3 and 9 (weak, medium and strong) was a conscious choice. Such scales are often used in Quality Function Deployment (QFD) analyzes - and the analysis in this thesis has many similar attributes to QFD. This MCA assesses how the three different scenarios perform at each of the nine success factors by allocating a weak, medium or high score for every cell in the table and summarizing the scores of each scenario to a total score.

The PBS sector delivers as mentioned earlier, solutions to office buildings, schools, hospitals, retail stores and similar. The size and demands to the BMS of these installations will vary a lot and the reference project used as reference in the CBA was used as reference for the MCA as well. An explanation of this reference project can be found in Appendix G.

Table 5.4: Multi-Criteria Analysis

Success Factor	Scenario 1	Scenario 2	Scenario 3
Suitable protocol stack for the size of the installation	3	3	3
Scalable network*	1	1	9
Capability to interoperate with other devices and systems	3	3	3
Sufficient range of communication	3	3	3
Sufficient reliability and speed. Minimal latency	3	1	3
Secure protocol stack	1	3	1
Competitive cost of installation and maintenance*	3	1	3
Fit device management requirements*	1	1	3
Aligned with the industry trends	3	3	9
Total Score	**21**	**19**	**37**

* Especially important for existing buildings

The table shows that Scenario 3 is the winner. This is the most future-oriented scenario and is totally wireless. Since this protocol stack is totally different from the current BMS protocol stack, it is not very likely that these three protocols will be the ones that operate in most BMSs in Europe in the next two till five years. But it is likely that some systems will and that there will be a tendency towards more use of the Bluetooth and the TCP/IP protocol (or a more specified IoT Internet protocol like MQTT) in professional buildings. In the following sections, the ranking of each success factor for each protocol will be described.

Suitable protocol stack for the size of installation. All of the scenarios is suitable for the reference project. Three floors and approximately 600 luminaire units is a suitable size for all the three protocol stack scenarios. Because of this, all the scenarios were given a medium score.

Scalable network. Scenario 1 uses KNX and BACnet at the automation and management level. Although these protocols come with a range of possibilities at the physical level, there would most likely be utilized one of the wired connection media solutions. Because of this, this scenario got a score of 1. Scenario 2 uses DALI at the field level which has a low degree of scalability. The third scenario is totally wireless and is highly scalable. This success factor is especially important for existing buildings as a scalable protocol stack easily can be implemented in an existing building.

Capability to interoperate with other devices and systems. All the protocols used in the scenarios are interoperable with other devices and systems. The scenarios got a medium score on this factor because there is not yet full, seamless, interoperability.

Sufficient range of communication. All the scenarios have a sufficient range of communication and were given a medium score. The scenarios did not get a high score because the range is not superior and many of the protocols can suffer from interference problems at present.

Sufficient reliability and speed. Minimal latency. Scenario 1 and 3 got a medium score on this success factor. This is because the Bluetooth protocol has a relatively high speed (and the field level speed is important for the total speed of the BMS). Scenario 1 uses KNX and BACnet which is seen to be reliable protocols and the same with Wi-Fi which is used in Scenario 3. All the protocols used in Scenario 1 and 3 also have low latency. Scenario 2 have gotten a low score at thus success factor. This stems from the slow speed of the DALI protocol.

Secure protocol stack. Scenario 2 got a medium score at this success factor. This is because this scenario uses the DALI protocol at the field level - and a wired protocol at this level is seen to be a secure choice. The two other scenarios got a low score. This is because of the use of the Bluetooth protocol at the field level. The Bluetooth protocol might be as secure as the DALI protocol but at present, this is not known to be a fact. The use of Wi-Fi is also seen to be less secure than to have a closed interface.

Competitive cost of installation and maintenance. The Bluetooth protocol will be more easy to program (each node will have its unique address), compared to using DALI at the field level (Sparkfun, 2018). With DALI one must be at the site and allocate ID numbers randomly when performing the programming procedure (Conversation, Laboratory Manager, 2018). Because of this, Scenario 1 and 3 got a medium score while Scenario 2 got a low score. This success factor has been labelled as especially important for existing buildings because the costs are often more weighted when only looking at the BMS compared to when the costs of the whole building are at question (as it is for new buildings and renovation projects).

Fit device management requirements. Scenario 3 got a medium score at this success factor because it is totally wireless and the devices of the BMS can therefore be moved around as preferred. The TCP/IP connectivity also makes remote access easy. Scenario 1 and 2 involves wires and is therefore given a low score. This factor is also labelled as especially important for existing buildings. This is because a protocol stack that fit device management requirements can easily be modified, upgraded etc. and an existing building with such a protocol stack is capable of handling future enhancement demands in the BMS.

Aligned with the industry trends. Scenario 3 got a high score at this success factor and is the only cell with a high score in the MCA. The high score was given because this is the most future-oriented scenario and because it is totally wireless. Scenario 1 got a medium score (Bluetooth is aligned with industry trends and KNX and BACnet is also somewhat aligned). Scenario 2 also got a medium score because of the use of Ethernet/Wi-Fi and Wi-Fi at the automation and management level.

There is of course also very important that the organization providing the systems operating on the given protocol has the competence to support their customers if any problems should occur. This factor has not been included as a success factor since the supply chain of the devices produced for the operation of professional buildings will vary a lot between enterprises.

In the next sub-chapter the different analyzes performed up till now will be compared and put together.

5.5 Comparison of the Analyzes

The three analyses presented in this chapter, Chapter 5, use different methods and data evidence. The three analyzes also ended up with somewhat different answers. This sub-chapter will compare and discuss the differences among these answers.

The questionnaire got 48 responses and ended up with Bluetooth, KNX and BACnet as the most probable protocols at the three levels of BMSs. The simplified CBA used the two top protocols at the field level for lighting from the questionnaire results as data evidence and concluded with the Bluetooth protocol for Glamox, the building responsible and the society and with the DALI protocol for the user. The MCA also used the questionnaire results as data evidence, more specifically the three scenarios constructed based on the questionnaire results. The MCA concluded with the protocols in Scenario 3, Bluetooth, Wi-Fi (TCP/IP) and Wi-Fi (TCP/IP).

In the execution of the three analyzes, we have thus moved from KNX to TCP/IP (with Wi-Fi at the physical layer) at the automation level and from BACnet to TCP/IP (with Wi-Fi at the physical layer) at the management level. Bluetooth keeps its strong position at the field level. As mentioned several times already there was found evidence from various reliable sources that there are reasons to believe that we will experience a transfer in the protocols used in the Internet protocol suite. A transfer from the TCP/IP suite to UDP/IPv6 suite. This transfer has however not been evaluated in the analyzes and is only supported by the literature evidence. In this regard it also has to be stated that if we get a transfer to the IoT Internet protocol suite using the IEEE 802.15.4 protocol at the physical layer, the Bluetooth protocol will probably not be needed anymore. Another possible scenario is that the IoT Internet protocol suite is built upon the Bluetooth protocol. Combining the analyzes and the written evidence is not a straightforward task and the readers of the thesis are encouraged to implement their own views and opinions when combining the analyzes and theoretical evidence presented in this thesis.

As mentioned in the description of the Bluetooth protocol in Chapter 3, the development of the protocol was driven by the cooperation of different (competing) enterprises and it was established a SIG. Getting a transfer to a standardized IoT protocol stack for professional buildings (and in general) will probably not happen before such a cooperation is established. There is also important to emphasize that defining a protocol stack using the full OSI model is essential in this context since having a standardized full ecosystem is desirable and since defining the top layer of the model, the application layer, is important in this context.

Kastner et al. (2005) stated that although investment in building automation systems will result in higher construction cost, their use is most economically feasible as soon as the entire building life cycle is considered. "Typically, the operational cost of a building over its lifetime is about seven times the initial investment for construction. Therefore, it is important to choose a building concept that ensures optimal life-cycle cost, not minimum investment cost" (Kastner et al., 2005, p. 1178). Taking this and the knowledge gained regarding the lack of interoperability in such systems into account, it is clearly a potential of saving a large amount of money for the individual enterprises and for getting towards a global system optimization if one standardized protocol stack for all BMS's is agreed upon.

The analyzes conducted in this chapter has suggested different BMS protocol stacks, some predictions in alignment with each other and some more contradicting. Which protocols are really the most likely to be included in this future protocol stack? The next chapter, the conclusion, will finally establish a concluding answer to this question.

Chapter 6

Conclusion

This master's thesis has established a theoretical framework, evaluated the global enterprise Glamox AS and analyzed important factors in the choice of communication protocol in lighting and building management. In this chapter, the main findings will be stated and a final answer to the RQ will be established. There will also be given explicit answers to all the seven SQs. The last two sub-chapters will evaluate the research design of the thesis and comment possible directions for further work.

6.1 Main Findings

Throughout this thesis, seven SQs has been answered, some in an obvious way and others more vaguely in the main text or in various tables and figures. The list below summarizes the most important features in these answers.

(a) *Which trends are emerging in the building and BMS landscape?*
Answer: The professional buildings are constantly changing and this thesis has found that we have a transfer from intelligent to smart to thinking buildings which again can be characterized as a transfer from reactive to adaptive to predictive buildings. The main contributor to this shift were found to be BMSs. The emerging trends in the BMSs were found to be more data (moving towards big data), increased focus on the top system (getting the sub-systems to function together) and increased use and focus on wireless technologies. We are moving from the traditional way of operation where each technical system have their own IT structure to integrated solutions where the BMS, consisting of both software and hardware, is configured in a hierarchical manner. The operator responsible for the buildings and the users of the buildings is starting to acknowledge what features that is possible to get through a more connected BMS and are starting to demand this from the enterprises producing the various technical systems in a building. This was however found to be a slow transition and most European buildings are currently not even intelligent. With the adaption of wireless technologies, it is possible to go directly from intelligent to thinking buildings. There was also found a trend towards a change in competition and in business models. Enterprises specialized on data collection or data analytics are entering the BMS market, with changes the competitive landscape.

(b) *What is interoperability and why is it important?*
Answer: Interoperability is the capability of devices of different types and from different manufacturers to exchange information via the communications network (ISO, 2004). In communication protocols, interoperability is the ability of different protocols to understand each other and since a communication protocol can be seen as a language made for a specific application or device type, interoperability is about the translation between the different languages (i.e. protocols). Achieving interoperability is important in both the general IoT environment and in the building management environment. According to McKinsey Global Institute (2015) interoperability is predicted to capture roughly 40 % and in some cases as much as 60 % of the potential value across IoT applications. Building management has generally been structured in silo applications where each technical system have had their own software. Optimizing the building as a whole have been a difficult task - difficult because of interoperability issues. The questionnaire had two questions regarding interoperability and found that 65 % agrees that there are often numerous different communication protocols operating at the same time in a BMS in a professional building and that close to 60 % agrees that it is often hard to achieve interoperability between the different protocols in BMSs. If one wants to utilize the full potential of the technologies currently available - getting full interoperability is essential.

(c) *What is the current competitive situation for Glamox AS in the IoT environment?*
Answer: There was performed a brief stakeholder analysis and a strategic analysis using the five force model of Porter to analyze the competitive situation for Glamox AS. The stakeholder analysis classified the identified stakeholders according to the Savage model. The technical building companies, electrical installation companies, technical installation companies and consultant companies were found to be supportive stakeholders. The users, suppliers, standardization organizations, employees, contractors, building owner and shareholders were found to have high potential to impact the organization and high potential for cooperation with the organization and thus to be "mixed blessing" stakeholders. Of these, the most dangerous stakeholders were found to be the suppliers, the standardization organizations, the contractors and the shareholders. This is because these are the most likely stakeholders to change the potential for cooperation with Glamox - and turn to the "non-supportive" stakeholder category.

The five force analysis found that the total competitive situation for Glamox was moderately in Glamox's disfavour. The main reason for this was found to be the bargaining power of suppliers, the threat of new entrants and the rivalry among the existing competitors. The most important factors in these negative forces were high bargaining power of suppliers of electrical (IoT) components and software, broadened product definition and the pressure from the new IoT products of the existing competitors. Two of the forces were found to be moderately in Glamox's favour. These forces were the "Bargaining Power of Buyers"-force and the "Threat of Substitute Products or Services"-force. The main positive factors in these forces are that increased product differentiation and closer customer relationship can reduce the bargaining power of the buyers and that the threat of substitute products or services might be reduced if continuing LMS success. The reader is directed to Chapter 4 and more specifically to Figure 4.1 and Figure 4.2 for further explanation.

(d) *What is the main differences between wired and wireless protocols?*
Answer: The main differences were found to be that wired protocols are more reliable, secure and suited for new buildings and renovation projects. Wireless protocols have lower installation costs, more flexibility and are suited for new buildings, renovation projects and retrofit applications. The disadvantages for wired protocols is that one must lay up the wires and that maintenance, updates etc. may be difficult. For the wireless protocols, the range and reliability issues were found to be the most important disadvantages. Table 5.1 summarizes the main differences and makes the comparison more visible.

(e) *Why is not "the Internet" used at all the levels of building management?*
Answer: The protocols currently used by the Internet is the so-called TCP/IP suite consisting of HTTP, IP, TCP and Wi-Fi or Ethernet. None of these protocols is made for the purpose of the IoT or managing devices in a professional building. Wi-Fi is an overkill technology in terms of speed and capacity and is way too power intensive to be used in transmitting sensor data. There are several good reasons for wanting to use the same protocol stack at all the levels of building management and there are currently several initiatives established to making this possible. The MQTT protocol, the transition to IPv6 and the use of the 6LoWPAN protocol combined with the IEEE 802.15.4 protocol has the potential to make this possible.

(f) *What is critical success factors for communication protocols used in building management?*
Answer: There were found nine critical success factors for communication protocols in building management. The communication protocol should: Be suitable for the size of the installation, provide scalability of the network, have the capability to interoperate with other devices and systems, have sufficient range of communication, have sufficient reliability and speed and minimal latency, be secure, have a competitive cost of installation and maintenance, fit device management requirements and be aligned with the industry trends.

(g) *Which light management protocol is most beneficial?*
Answer: The questionnaire concluded that Bluetooth (36 %) or DALI (30 %) was the most probable protocols at the field level for lighting. There was performed a simplified CBA in order to find which of these two protocols that would be most beneficial. The CBA found that the Bluetooth protocol would be most beneficial for Glamox, the building responsible and for the society and that the DALI protocol would be most beneficial for the users of the building. The total aggregated result from the CBA was that the Bluetooth protocol was three units more beneficial than the DALI protocol.

The sum of the SQ-answers forms the basis of the final conclusion of this thesis, the answer of the RQ:

"Which communication protocol is most likely to become leading in the light management systems in the professional building market in Europe during the next two till five years and which other communication protocols should the light management protocol be able to interoperate with?"

Final Conclusion: Several analysis methods were used to find the answer to this question. If we first take a look at the most likely protocol for light management, the following was found: The questionnaire concluded with Bluetooth and the simplified CBA concluded with Bluetooth for Glamox, the building responsible and for the society and with DALI for the user. The MCA concluded with Scenario 3, i.e. Bluetooth. The RQ does not ask about a specific stakeholder but for the general case and combining the three analyzes gives Bluetooth a strong position, and is seen to be the most likely protocol for LMSs in Europe during the next two till five years. The second part of the RQ asks about which protocols the light management protocol should be able to interoperate with. The questionnaire found that the most likely protocol at the automation level is KNX or the TCP/IP suite and at the management level BACnet was found to be most likely, followed by the TCP/IP suite with Wi-Fi at the physical level as most likely. The MCA compared three scenarios that were put together based on the questionnaire results and had a strong conclusion towards Scenario 3 which uses Bluetooth and the TCP/IP suite. The building specific protocols like KNX and BACnet and the current Internet protocol suite, based on the TCP/IP suite, has been found to be a poor fit with IoT applications and the future demands of BMSs and it looks like we are moving towards a more IoT-suited protocol stack using protocols such as IEEE 802.15.4, 6LoWPAN, MQTT and UDP. Therefore, this thesis concludes that the light management protocol should be able to communicate with the future Internet protocol suite based on the transfer to IPv6.

Digging into communication protocols used in professional buildings has made several eye-opening aspects visible. One of them is the fact that no matter how much effort is added into finding the protocol that is best-suited for a given application - comparing important measures as range, bandwidth and security performance - it is not necessarily the best suited protocol that will be chosen in the end. Brand name and the so-called goodwill of the different protocols were in many cases found to be just as important or even more important than the technological performance. Another important aspect is the focus on waiting for the customer to demand more advanced IoT technologies instead of providing the solution before the demand occurs and possibly getting a “wow effect” and competitive advantage. There was also found many contradicting views and a lot of biased information. Enterprises with interests in one specific protocol will keep using and promote their protocol as long as possible, even though this protocol clearly is not the best choice because they are so afraid that transferring to another protocol will cause more trouble than the benefits it gives.

The technology development will stagnate and we will be stuck with wall switches, too hot and too cold classrooms, blended eyes when writing on our office laptop and unpredictable, high energy bills, just to mention some, if we do not change the way BMSs is structured and the way the involved actors communicate. Since this thesis has used Glamox as case enterprise, some well-considered words of how they can be a part of transforming the industry to the better for the enterprises, the building responsible, the users and the society will now be given. Bluetooth (2018) stated that wireless lighting solutions can function as a platform to further enable point-of-interest solutions, indoor navigation, asset tracking, and space utilization in the smart building. Connected lighting emerges as a key use case in automation and Glamox has thus the potential to form how the future BMSs should become. Glamox should take action to be involved in standardization initiatives and promote the use of open standards and software source code. They should also initiate communication with the other technical building actors. If we can get to a point where the optimization starts at the production hall instead of in the building, there is true potential for arriving at the "intelligent building"-stage during the next decade.

6.2 Evaluation of Research Design

This research has used several different methods in order to gain the evidence needed. Using a general literature review and a case study was found to be a suitable methodology for the purpose of this thesis. The questionnaire is seen to be an important contribution to the thesis and sheds light on an area with much biased and not publicly available topics of research. One can thus say that it fills a gap in this area of research/literature. There should, of course, be emphasized that there would have been preferred to have collected more responses to strengthen the conclusions taken from the questionnaire even more. With the resources and the time available, 48 responses are nevertheless seen to be a high number of responses.

The methods used to analyze the evidence found in the primary and secondary sources should also be commented. Even though a triangulation in analysis methodology was used, the actual methods were simplified or used to a low extent. Both the CBA and the MCA includes several uncertain elements which should be taken into account when evaluating this research.

6.3 Further Work

This work has found what would be the most probable communication protocol in LMSs in the professional building market in Europe during the next two till five years and which communication protocols the light management protocol should be able to interoperate with. There exists a range of different directions that a further work could take, some a continuation of this work and some totally new directions, as for instance:

- *Conduct a full CBA.* Since the CBA conducted in this research is totally non-monetary there would have been useful to find true monetary values of the different posts.
- *Look at national and continental differences.* This research is situated in Europe and mainly Northern-Europe. Looking at differences in protocol preferences in a selection of different countries and continents would be interesting for enterprises operating in the BMS area since most of them also operate on several geographical markets.
- *Take the perspective of another technical building actor.* Using another or several other technical building actors as HVAC, security, lift, etc. would give the research a more solid ground and could give the possibility to conduct an in-depth benchmarking study.

- *Look at an old, an up to date and a future professional building and benchmark important measures.* This would be an interesting historical journey, looking at the change in both technology and human demands.
- *Make test rigs of the most probable scenarios used in this thesis.* Depending on the size and comprehensiveness of the test rigs, this analysis could possibly produce enough evidence and user data for finding what protocol stack is most likely to become the industry standard.

The bullet point list over is only suggestions of possible directions of further work and it would not surprise the researcher if other interesting directions are found. This is a highly evolving theme of research and there is a possibility that a protocol not even mentioned in this thesis can pop up and take the whole IoT market. Enterprises and individuals interested in IoT communication protocols should keep their eyes and ears open and stay alert.

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Appendices

Appendix A

Literature Review Screening Process

The flowchart is shown on the next page and will be described here. The oval shapes on the flowchart represent a start or stop. The rectangular shapes is a description and the diamond shapes is a decision node. As can be seen from the chart, the literature review screening process started by making an Oria/Google search with relevant keywords. Then, the search result was screened chronologically and a decision of whether the title/preview seemed to be relevant was taken. If the title/preview was seen to be relevant the abstract/first part was read. After this, a decision of whether the abstract/first part was interesting for the thesis scope was taken. If it was seen to be relevant, the conclusion/last part was read and again a decision of whether it was relevant or not was taken. If the conclusion/last part was found to be interesting, the whole study was read and the most important parts/sections were marked. Relevant parts of the evidence source were implemented into the thesis document and archived. Then, the researcher returned to the search result and if there were any entries left in the search result, the screening started again. If, however, the given entry was seen to have a non-relevant title/preview, abstract/first part or conclusion/last part the flowchart leads to the decision node about whether there were any entries left in the search result and back to the search result or to a new search, accordingly. The flowchart is made as a continuous, never-ending, loop and the literature review was, in fact, continuous throughout the thesis' writing period. However, it has to be stated that the literature review was frequently stopped because other means of the thesis had to be implemented and investigated.

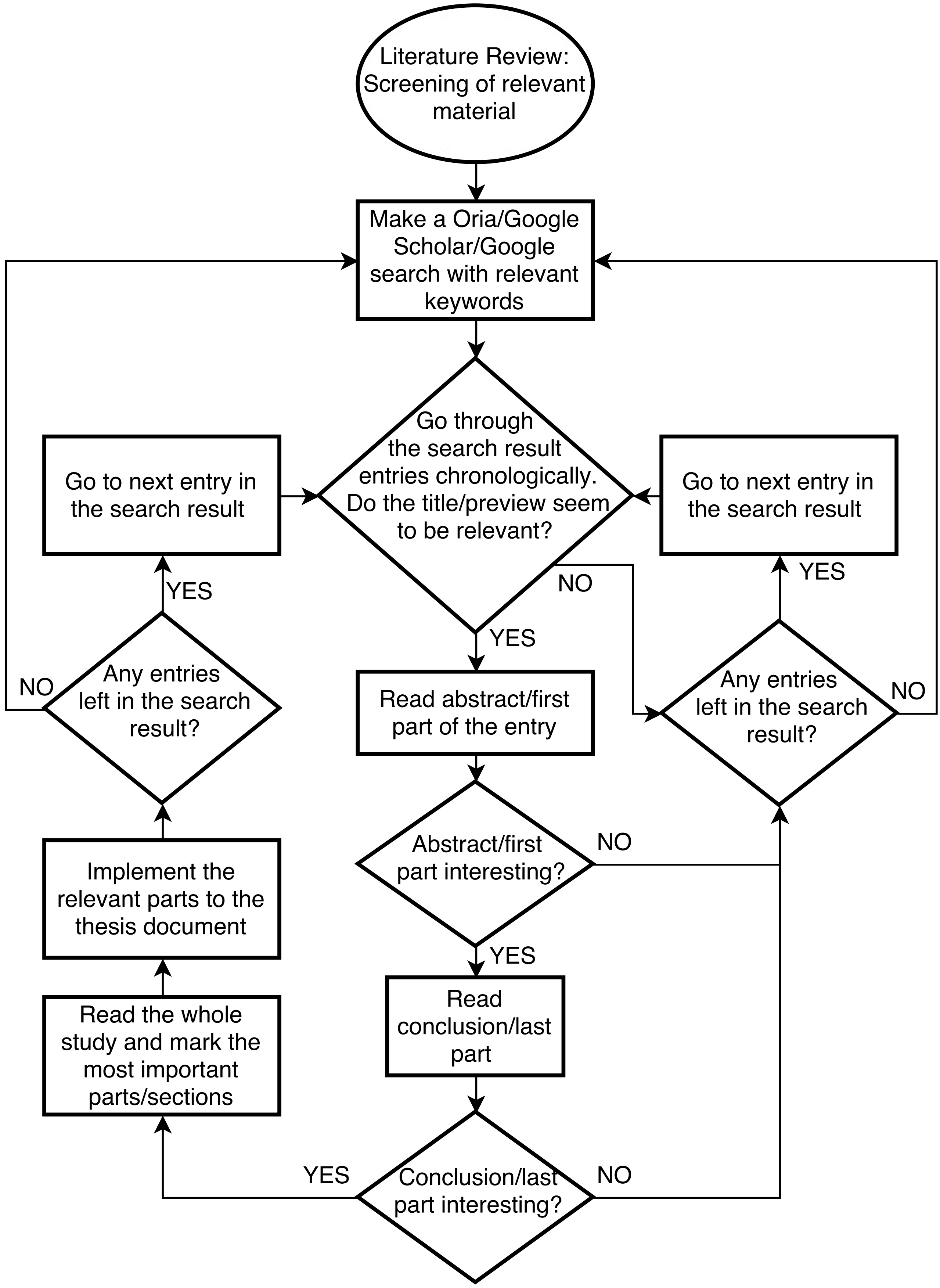


Figure A.1: Flowchart of literature review screening process

Appendix B

Questionnaire

This appendix describes the general impression the researcher had of the conduction of the questionnaire and displays the questionnaire sheet.

General Impression
The questionnaire was constructed in March and got a total of 48 responses. Since the researcher was present during the submission of the questionnaires, the respondents had the possibility to ask questions if anything was unclear. The general impression is that the questions was well formulated and all together well understood by the respondents. However, there is a few aspects to comment. Q1A had some uncertainty regarding what "change" it was referring to. This "change" could therefore have been specified more. Q1B and Q1C was well understood by all the respondents. Q2 had a few uncertainty aspects. Some of the respondents were uncertain about what the "automation level" was but were satisfied with the explanation given by the researcher. The figure was overall well understood. Some of the respondents misunderstood the question and ticked which layer the protocol they knew belonged to and did not answer the question who asked about the future aspects. When corrected by the researcher they understood, and changed their answer accordingly. In retrospect, the protocols IEEE 802.15.4, MQTT, UDP and 6LoWPAN should have been included as alternatives in Q2. The researcher thinks however that the results would not have been different to any large extent, since these protocols are relatively new and unfamiliar to most building management representatives. Q3 were by many of the respondents not answered because they seemed to overlook it. The researcher did not push the respondents to answer this question because it is a partly sensitive question and because it was not seen to be that important for the final conclusion.

Questionnaire: Communication Protocols in Building Management Systems (BMSs)

This questionnaire is made as a tool for gaining source data to my master's thesis written at the Department of Mechanical and Industrial Engineering at the Norwegian University of Science and Technology during spring 2018. It will take maximum 5 minutes to complete this one-page questionnaire. Your responses will be treated in confidence and will be used only as part of this research project. Your anonymity will be respected and there will be nothing in the results that might connect you or enable others to connect you to the data. Please do not hesitate to contact me if you have any questions regarding the questionnaire on email, ritagn@stud.ntnu.no, or mobile, +47 99582827.

1. Tick the cell that you think is most correct for the statements (1a-1c).
   a) Connecting "Everything" to the internet is one of the largest trends in today's digital society, often named by the buzzword "Internet of Things" (IoT). How much do you think the IoT will change the current BMSs?

Total change	Large change	Some change	Small change	No change

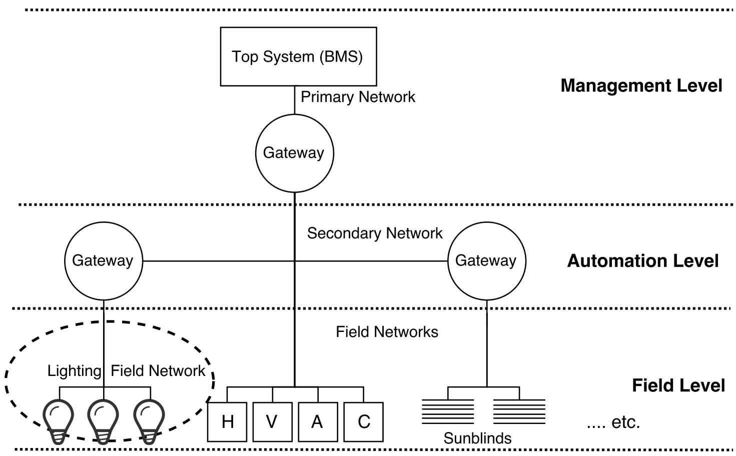
   b) There are often numerous different communication protocols operating at the same time in a BMS in a professional building.

Strongly agree	Agree	Neutral	Disagree	Strongly disagree

   c) Getting interoperability between the different protocols in the BMS is often hard to achieve.

Strongly agree	Agree	Neutral	Disagree	Strongly disagree

The figure below illustrates the three layers of BMSs and a typical system architecture. In order to have a common reference, the figure should be used to answer question 2.



2. Communication protocols is the set of rules and formats regulating the information exchange between the elements of a system and is in the BMS context used in the primary, secondary and field networks. What is in your opinion the most probable protocol in the Management, Automation and Field Level for lighting (see dotted circle in the figure) for the BMSs in the near future (2-5 years). Please tick only one protocol per layer (one tick per row). If you choose "Others, please specify" please write the name of the protocol in the given cell of the table.

	Communication protocol									
Level of BMS	BACnet	LonTalk	KNX	Wired DALI	Bluetooth Mesh	ZigBee	Z-Wave	TCP/IP WiFi	TCP/IP Ethernet	Others, please specify
Management										
Automation										
Field (Lighting)										

3. Please write your current working title on the line: ____

Thank you for taking the time to answer this questionnaire!

Rita Nerland

Student NTNU

Appendix C

Questionnaire Graphs

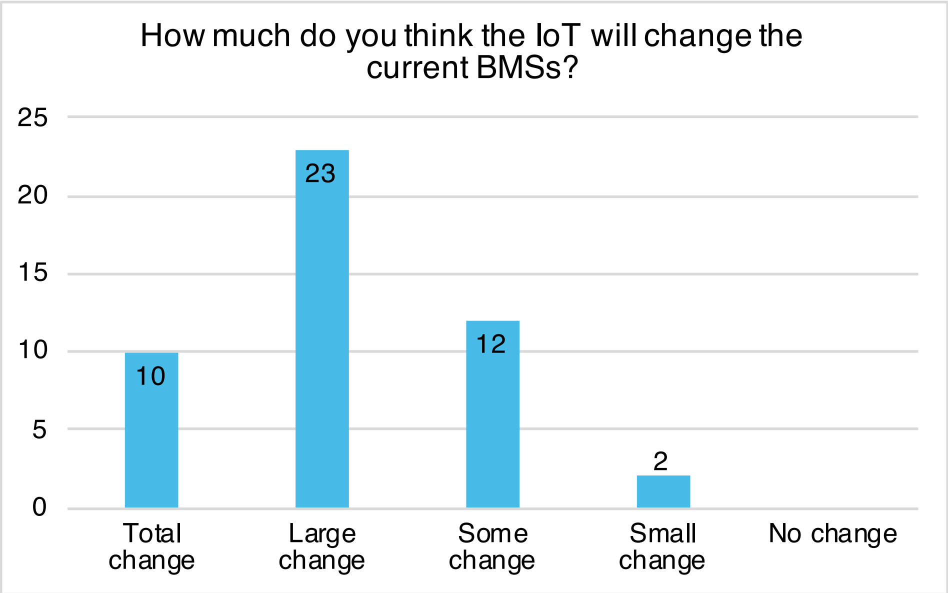


Figure C.1: Full size bar chart of Q1A responses

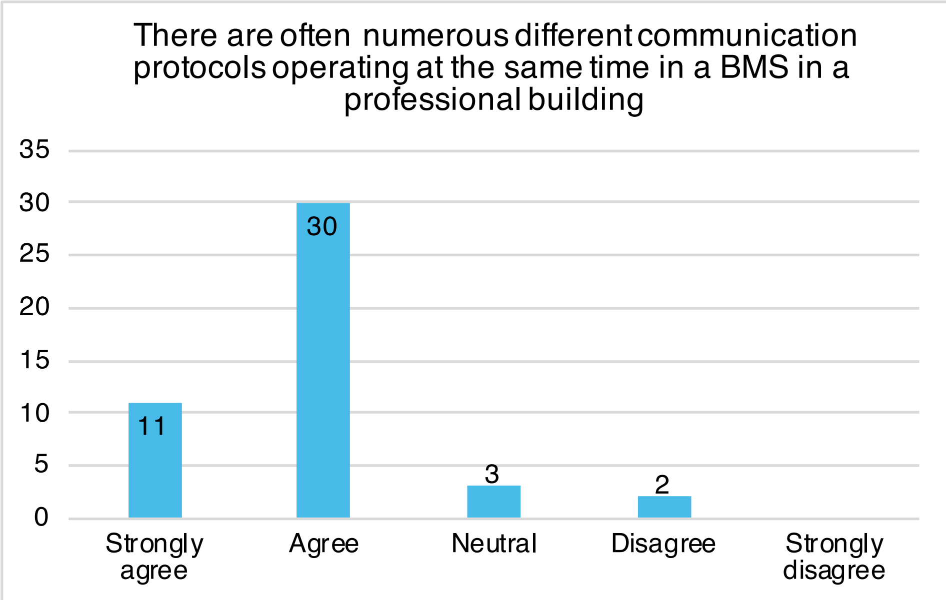


Figure C.2: Full size bar chart of Q1B responses

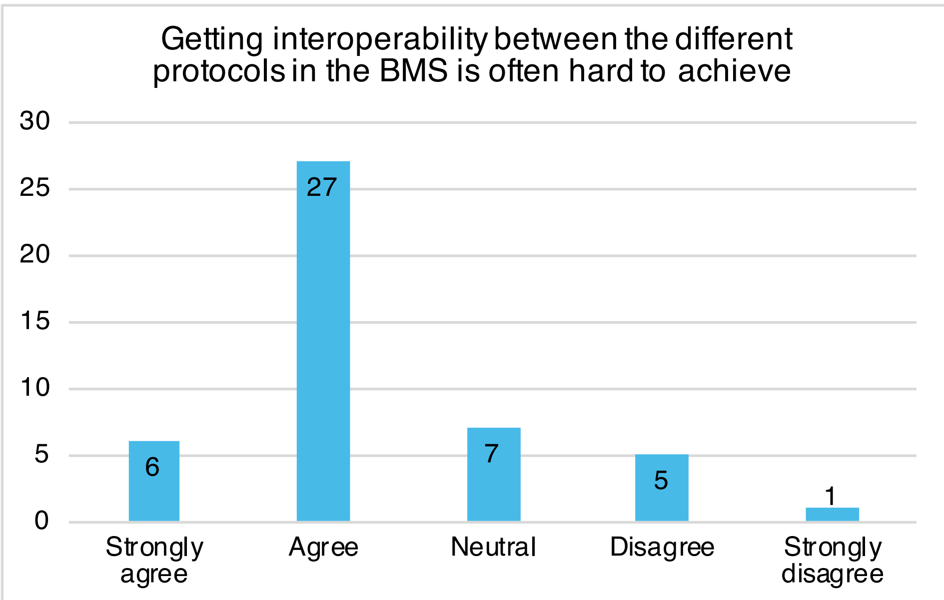


Figure C.3: Full size bar chart of Q1C responses

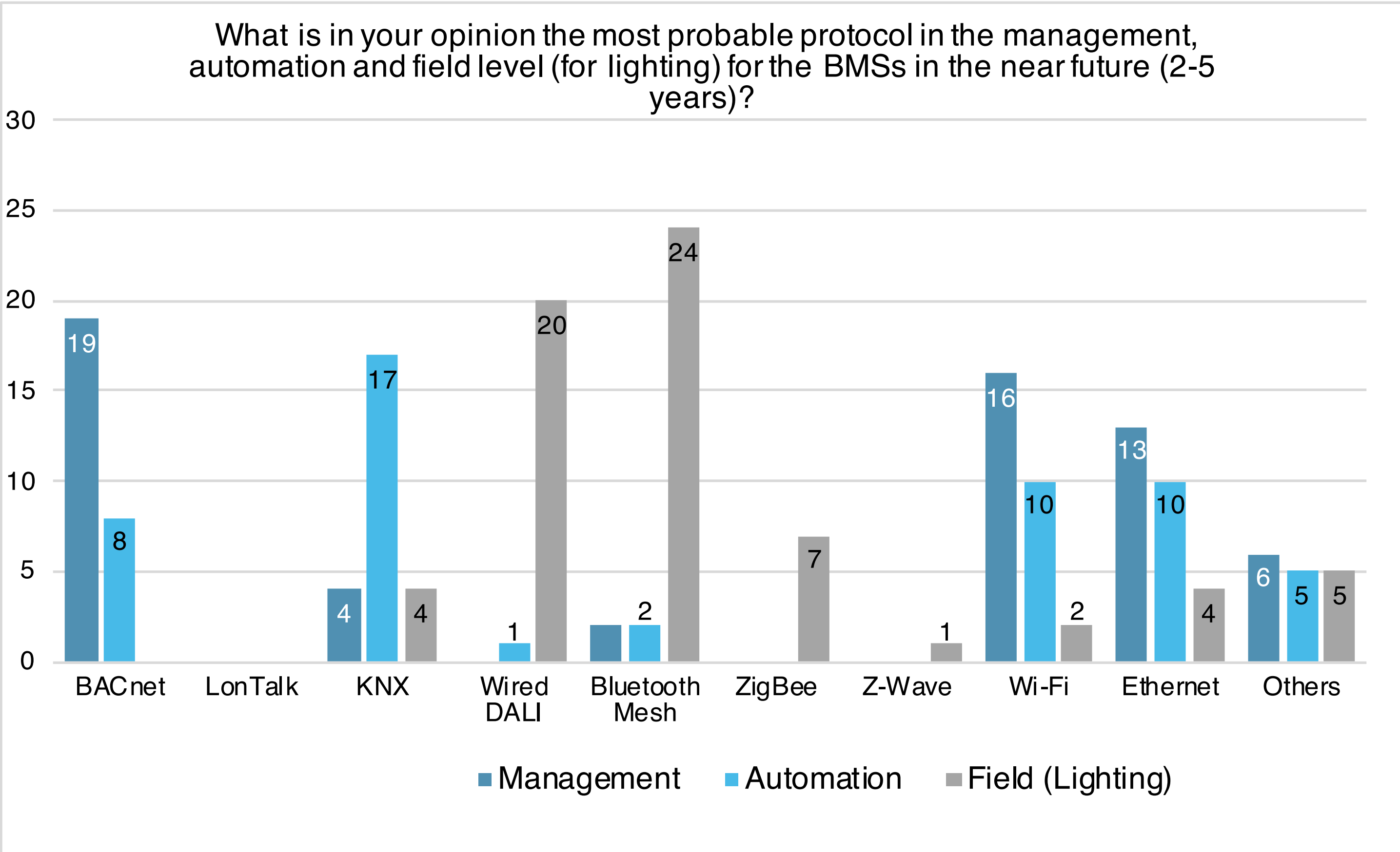


Figure C.4: Full size bar chart of Q2 responses

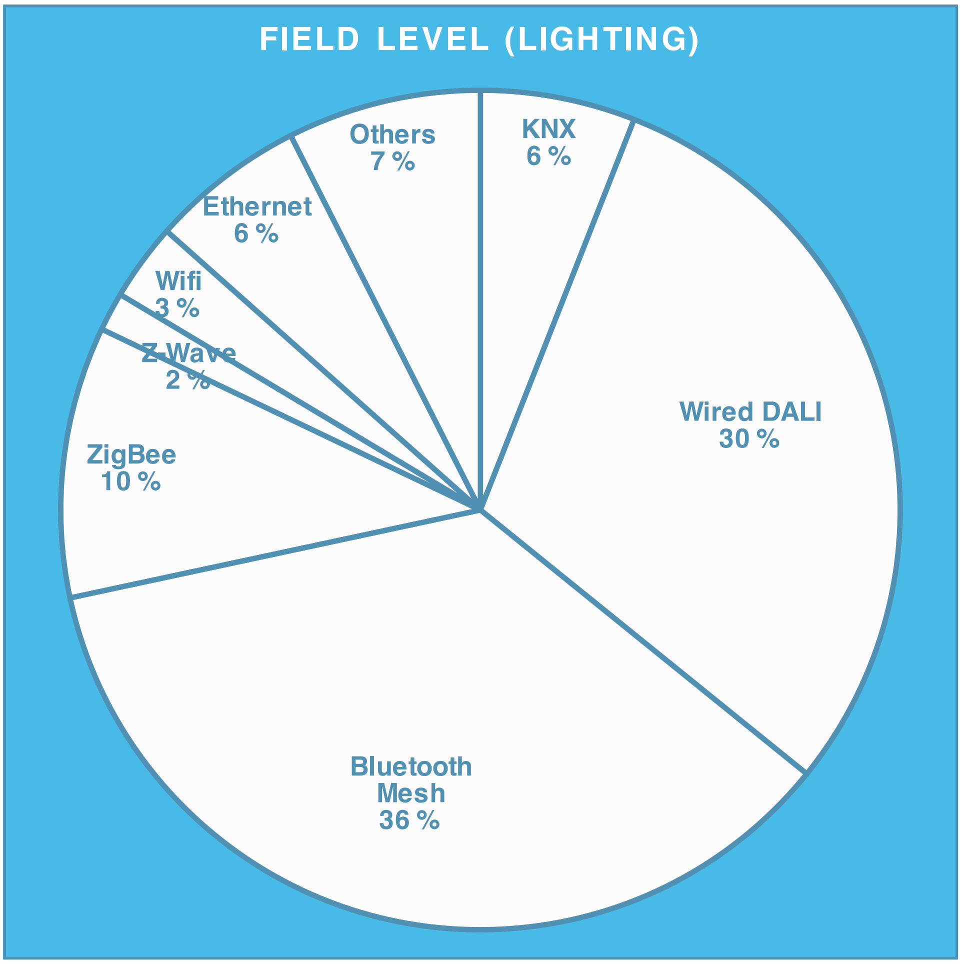


Figure C.5: Sector diagram of field level responses

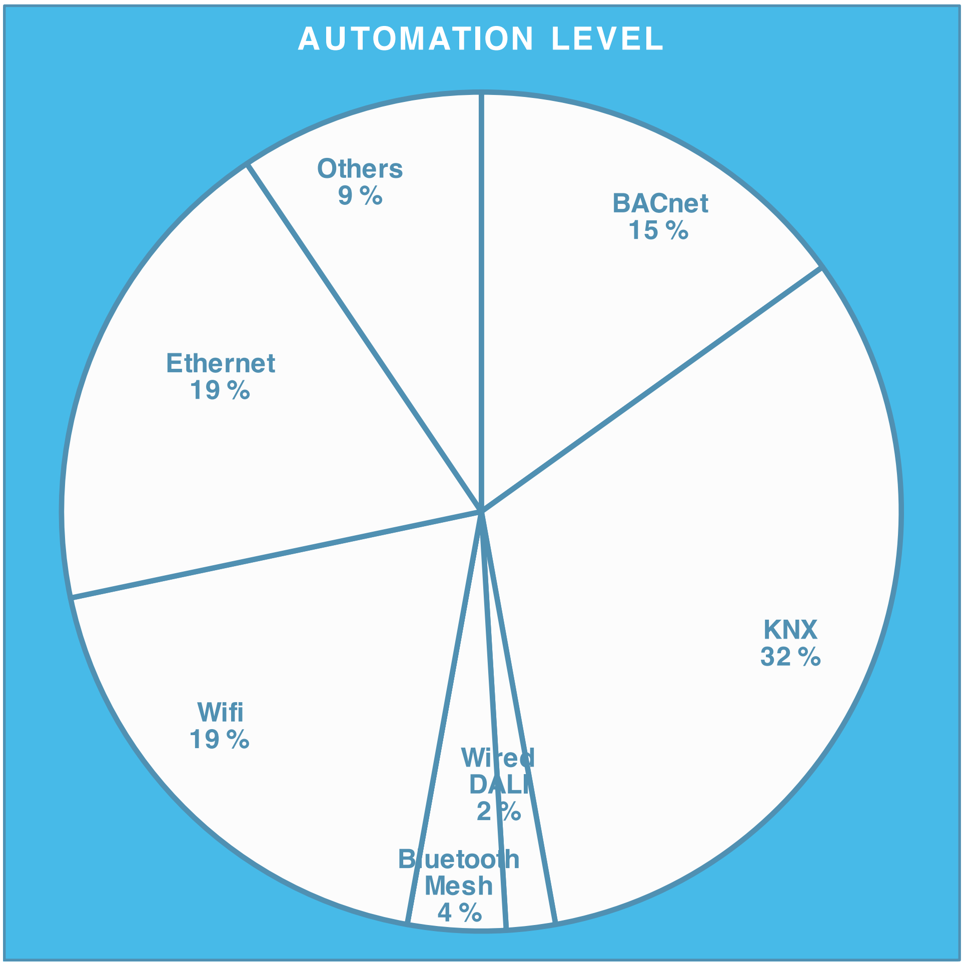


Figure C.6: Sector diagram of automation level responses

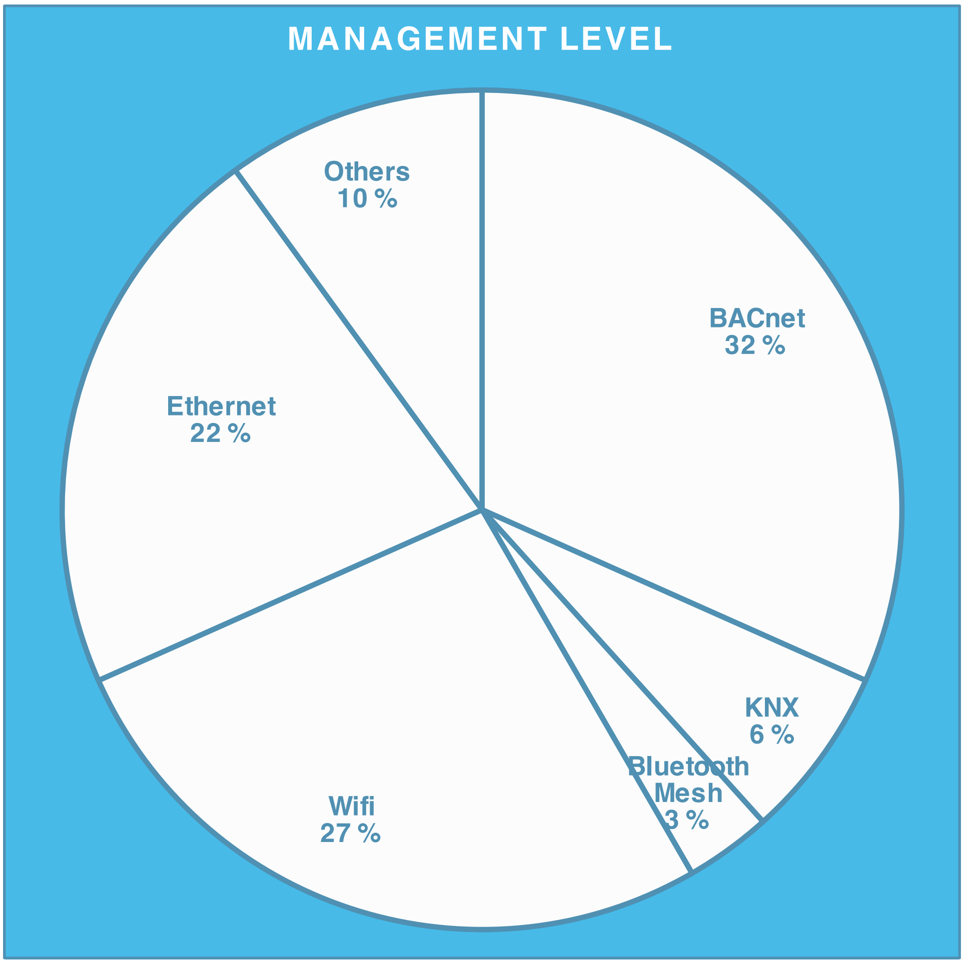


Figure C.7: Sector diagram of management level responses

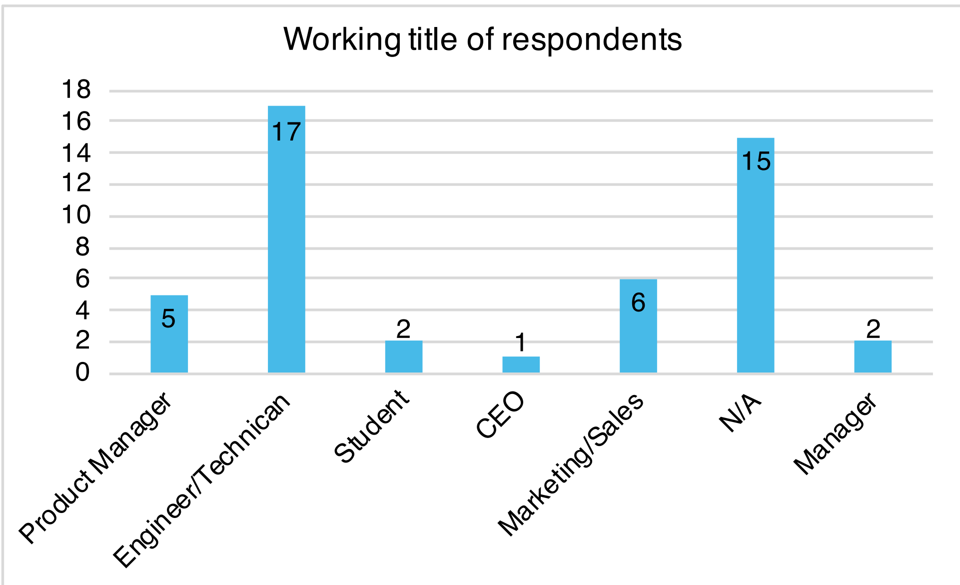


Figure C.8: Full size bar chart of Q3 responses

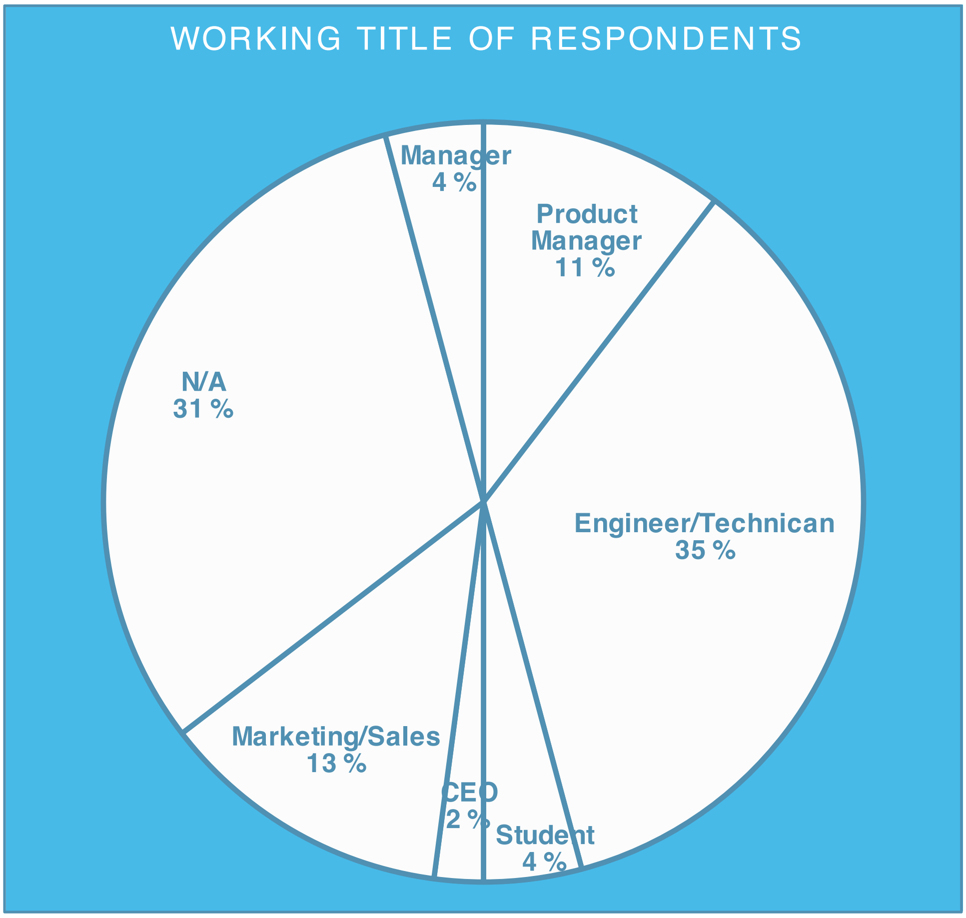


Figure C.9: Sector diagram of Q3 responses

Appendix D

Glamox Wireless

The Glamox Wireless brochure is presented in the following pages.

Glamox Wireless

You define. We connect.

Light management systems for the future

Glamox Wireless is part of the Glamox Light Management Systems portfolio. Below you can read about some of the advantages associated with our systems.

A light management system from Glamox is a beneficial choice, whether you are the end user, the building owner, the installer, the facility manager or the consultant. Our solutions are:

Easy to plan

On your local Glamox website you will find a LMS solution guide. Here you can find LMS solutions for different applications in your segment along with suggestions for floorplans and lists of the components you need with their article numbers. LMS is also an integrated part of our light calculation tool. This ensures detailed and accurate LMS documentation that is updated when changes are made in the plans for the light installation.

Easy to commission

We want you to feel confident when you select a LMS system from us. By using Glamox commissioning services, you are granted that we take full system responsibility for the total lighting solution. The commissioning is done by highly competent system integrators that are trained in the Glamox systems.

Easy to use

When designing our light management systems, we have put high emphasis on creating intuitive user interfaces. Most of the time the end user will experience our light management system as "Invisible technology" that allows the lighting to adapt to their needs.

Easy to install

By using established standards and technologies that are well known to the installers, we pave the way for a problem-free installation.

Connecting things that matter

Glamox is following the technological trends closely, and will consecutively implement the most relevant IoT technology, that gives real value. We want to ensure that the best technology is always available to our customers.

Flexible

With programmable, addressable luminaires and control gear, a solution can easily be adapted to new needs without doing physical changes to the installation.

A warranty for quality

We provide a safe choice. Our solutions are tested for compatibility in our laboratory. 70 years in the lighting industry has helped us build a lot of competence and taught us the value of quality. This is one of the reasons why we only work with the best suppliers and partners.

Why Wireless?

With wireless technology, the light management system becomes extremely flexible. No need to rewire, just change the set up and the solution is adapted to a new interior layout instantly. To the refit market this is an enormous advantage.

Whether Glamox Wireless is for industrial or general purposes it will always be possible to connect it to Ethernet and then translate data for use in a central monitoring system. By using a central access point, we can also offer added services such as monitoring energy consumption and emergency lights.

Central monitoring

A central monitoring system will help you monitor and control the energy consumption from lighting. It is also the best tool for optimising lighting for different purposes, especially when you're managing a diverse building.

Single Group Multiple Group Central Monitoring

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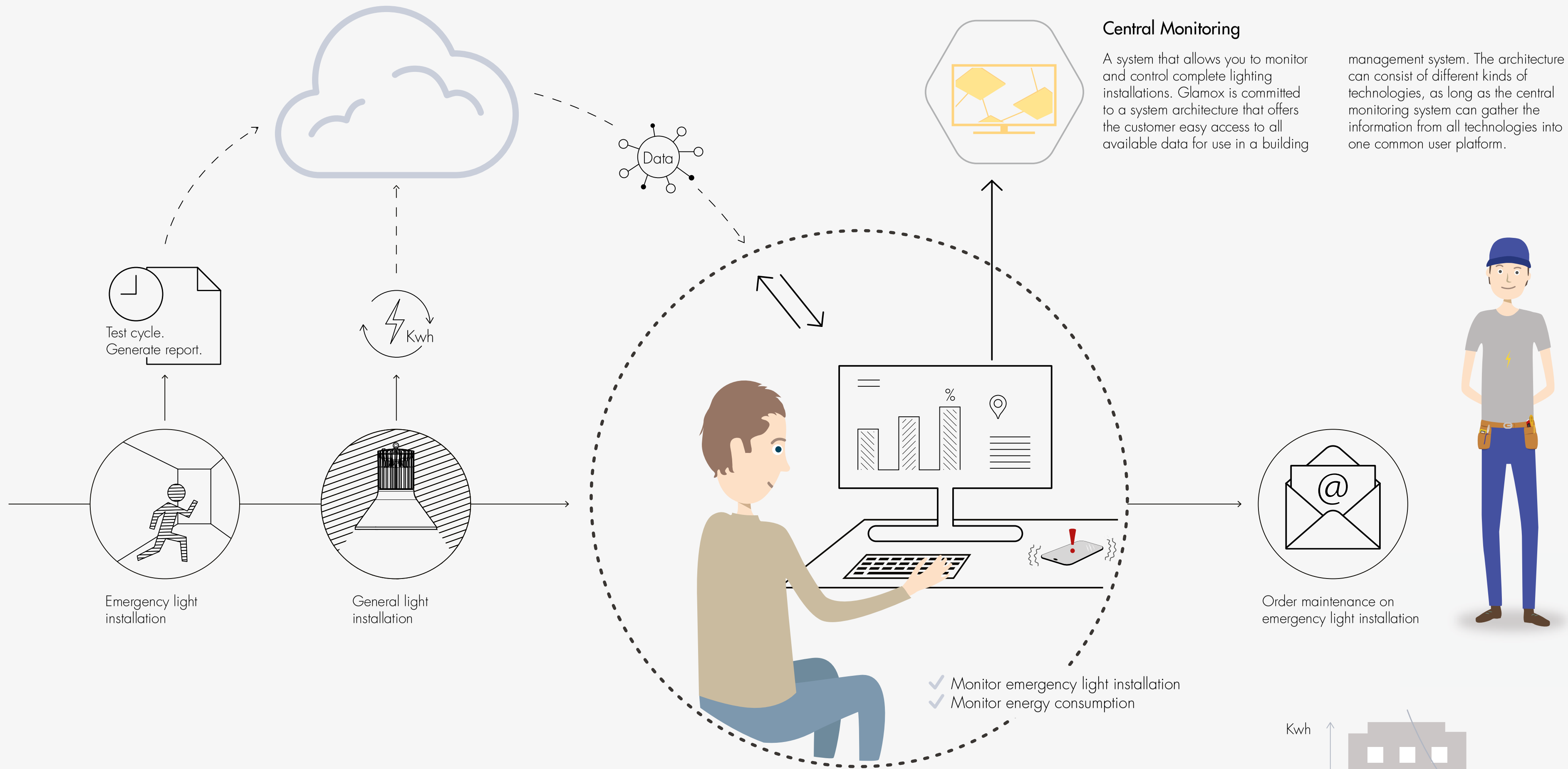


Central Monitoring

A system that allows you to monitor and control complete lighting installations. Glamox is committed to a system architecture that offers the customer easy access to all available data for use in a building management system. The architecture can consist of different kinds of technologies, as long as the central monitoring system can gather the information from all technologies into one common user platform.

Monitoring emergency lightning

Say goodbye to time-consuming emergency light inspections. By using a wireless addressable emergency light system, it is possible to set up test cycles and generate/save reports that fulfill European and national standards. When something is wrong an e-mail can be sent to the responsible maintenance personnel.

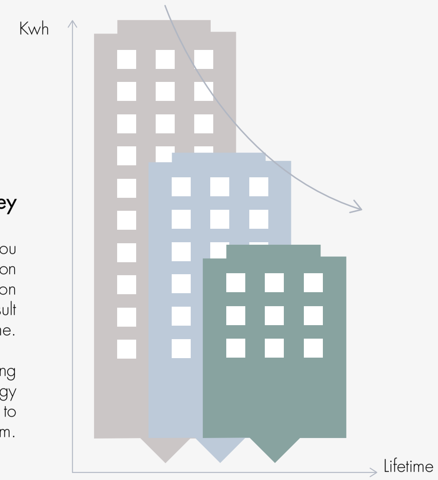
Easy mapping of energy consumption

Our central monitoring system provides an easy user interface for monitoring the energy consumption in the building. Also includes heat mapping that can visualize the energy consumption in different areas of the property in order to see how well the system is performing and adjust accordingly.

Smart way of saving money

By investing in a Glamox wireless system you will save money both on the electricity bill and on maintenance. Put in other words: the lighting installation uses less kilowatt hours each month and, as a result of reduced usage, achieves a longer product lifetime.

An energy reduction of 60 percent and a doubling of the lifetime is not uncommon. Try our smart Energy calculator that allows you to explore the ROI related to an investment in a wireless light management system.



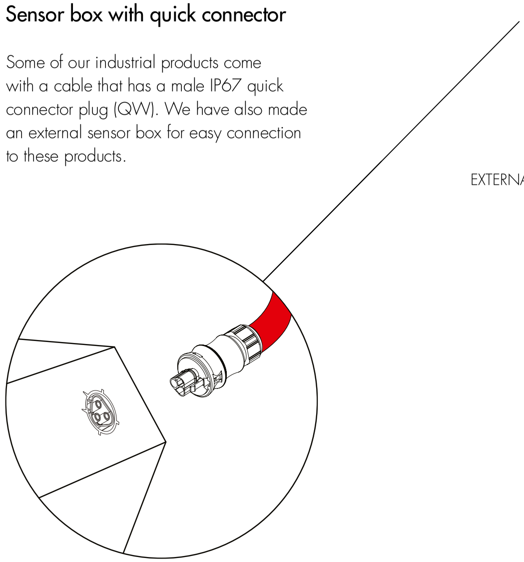
Easy to install

The complexity of the installation often increases with the flexibility of the LMS system. However, Glamox Wireless offers a modern and flexible LMS solution that is as easy to install as a standard on/off installation.

External sensor box.

Sensor box with quick connector

Some of our industrial products come with a cable that has a male IP67 quick connector plug (QW). We have also made an external sensor box for easy connection to these products.

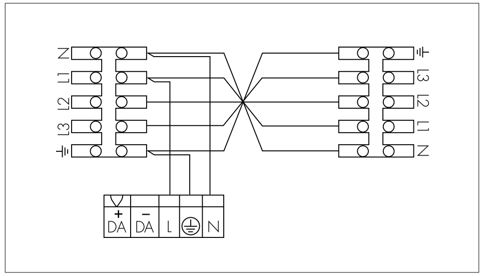


External sensor box for through wiring

EXT IW-SEN TW M25

2x5x4 mm²

The sensor box has connection for 5-wire DALI wiring to a luminaire, and 3-phase trough wiring, 2x5x4mm² for mains. Cable entry for the mains in/out are two M25 glands.



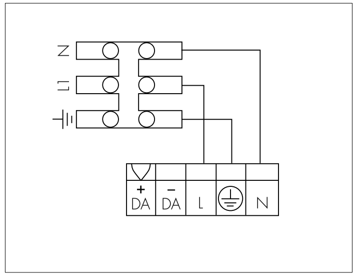
EXTERNAL SENSOR BOX

External sensor box

EXT IW-SEN M20

3x2,5 mm²

The sensor box has connection for 5-wire DALI wiring to a luminaire, and 1-phase termination, 3x2,5mm² for mains. Cable entry for the mains is a M20 gland.



EXTERNAL SENSOR BOX

*Samsung Tablet A

Luminaires with an integrated wireless sensor

Glamox C51-S

Sports halls

Sports halls are often used for more than sports. To accomodate activities like exhibitions, social events and even concerts the flexibility offered by Glamox wireless is the perfect choice.

Glamox GIR

Applications for open luminaires (< IP55)

For use in warehouses, assembly lines and similar applications. Glamox wireless will halve the energy consumption and double the lifetime of the installation.

Glamox MIR

Applications requiring closed luminaires (> IP55)

Parking houses and industrial plants are often in use 24/7. By using Glamox wireless the lifetime of the luminaires will be more then doubled without having to rewire the installation.

Connecting different external sensor boxes

For high bay applications

Industrial facilities with high ceilings is often associated with complex and expensive lighting installations. With Glamox Wireless you can get the same flexibility as with modern control systems without spending time and money on cabling.

Glamox A90

A decorative and tough luminaire with a design that satisfies both the requirements posed to an industrial luminaire and the high demands made by architects and light designers when it comes to aesthetics and functionality. Mounting heights up to 10-12 metres.

Glamox i95-P

A robust IP65 luminaire with accurate light distribution. The product can be pendant or surface mounted and is designed for applications like production premises, warehouses, entrance halls and atriums with mounting heights up to 10-12 metres.

Glamox i90-P

A robust and powerful IP65 LED luminaire for demanding industrial applications. The product can be pendant or surface mounted and is designed for challenging production premises, distribution centres and high bay warehouses up to 25 metre mounting high. Can be used in ambient temperatures from -40°C up to 60°C.

Glamox i80

A family of IP66 industrial LED luminaires for surface and pendant mounting or in open ceilings by using a recessing frame. Can be used in ambient temperatures (Ta) from 50°C down to -40°C.

External wireless sensor box

The external sensor box can be connected to industrial DALI luminaires. It can also be used as a connection box for distributions of 3 phase mains. This is when choosing a Through Wire (TW) solution. Most of our industrial high bay luminaires comes with a 2-metre cable as standard.

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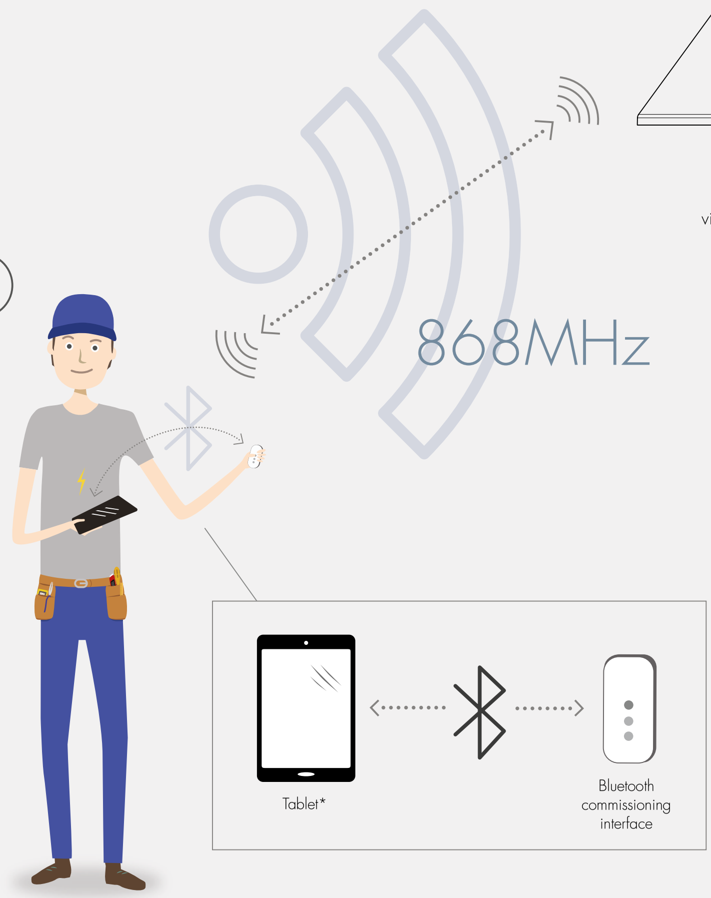
Easy commissioning

By using a tablet* as commissioning tool you can always be present in the actual room while doing the commissioning. A gateway, the Bluetooth Commissioning Interface, is used to translate from Bluetooth to the 868MHz used in the Glamox Wireless system.

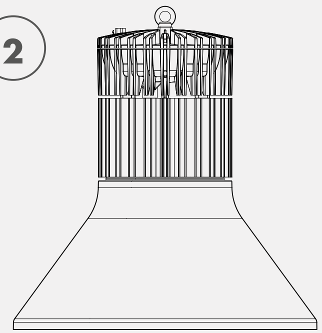
1



Installer

The Bluetooth commissioning interface is found automatically by the tablet`s Bluetooth interface. Open the Glamox Wireless software and start the commissioning.

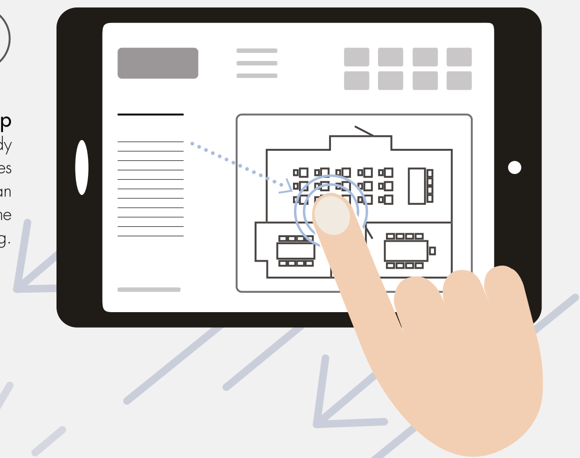
2



Find the luminaires

Click "Find" and the system visualises the 5 closest luminaires, based on signal strength.

3



Drag and drop

A drawing in bitmap is already uploaded. The 5 closest luminaires are identified and then you can simply drag and drop them to the correct place in the drawing.

4

Make groups

After identifying all luminaires in a room you can easily divide them in different groups just by drawing a square containing the appropriate luminaires.

5

Set parameters

Finally you set the parameters according to the functionality you want. Time delays, values when present or absent, daylight control or even manual override.

6

Finished

You are now ready to start using your Glamox Wireless system.

*Samsung Tablet A

GLAMOX

The Glamox Group

Glamox is a Norwegian industrial group that develops, manufactures and distributes professional lighting solutions for the global market.

Quality brands and solutions

The Group owns a range of quality lighting brands including Glamox, Aqua Signal, Luxo, Høvik Lys, Norselight and LINKSrechts. Glamox is committed to meeting customer needs and expectations by providing quality products and solutions, service and support.

Technology and expertise

Our products and solutions are developed and tested by our engineers at our own research and testing facilities, and manufactured and certified in accordance with all relevant quality and environmental standards. They are based on the latest technology and expertise – and generations of experience.

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www.glamox.co.uk

Appendix E

Questionnaire Result Table

Table E.1: Questionnaire result table

Question	Category/Number of Answers									
1a	Total change	Large change	Some change	Small change	No change					
	10	23	12	2	0					
	Strongly agree	Agree	Neutral	Disagree	Strongly disagree					
1b	11	30	3	2	0					
1c	6	27	7	5	1					
2	BACnet	LonTalk	KNX	Wired DALI	Bluetooth Mesh	ZigBee	Z-Wave	Wi-Fi	Ethernet	Others
Management	19	0	4	0	2	0	0	16	13	6
Automation	8	0	17	1	2	0	0	10	10	5
Field (Lighting)	0	0	4	20	24	7	1	2	4	5
3	Product Manager	Engineer/ Technican	Student	CEO	Marketing /Sales	N. A.	Manager			
	5	17	2	1	6	15	2			

Appendix F

Illustration of Scenario Architecture

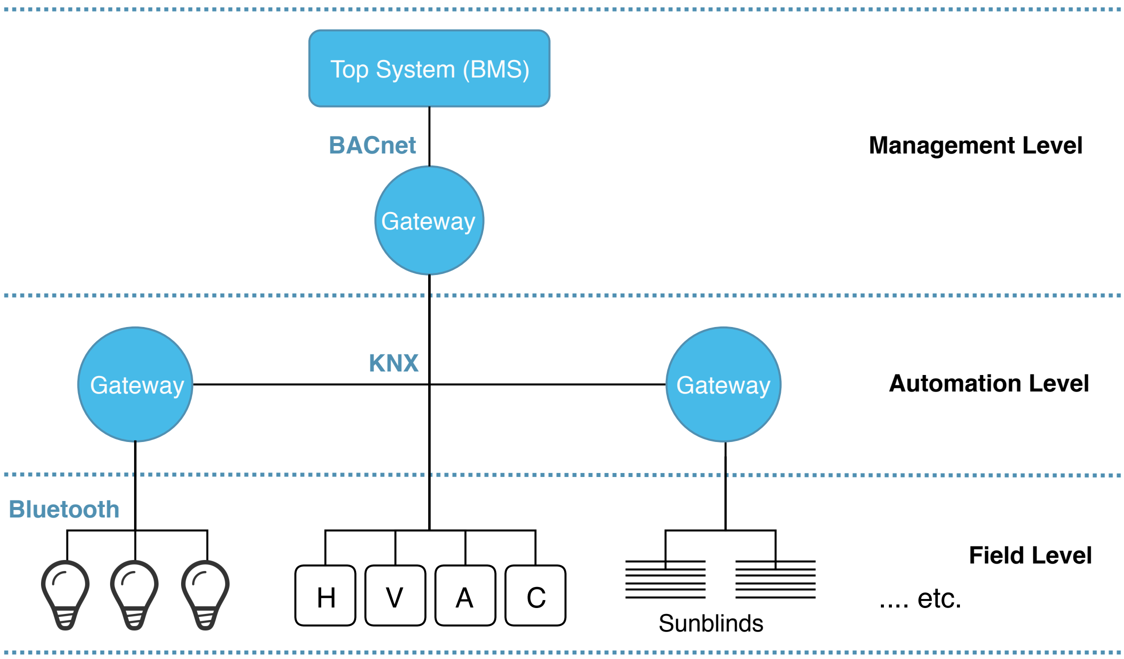

Figure F.1: Scenario 1: Bluetooth, KNX and BACnet

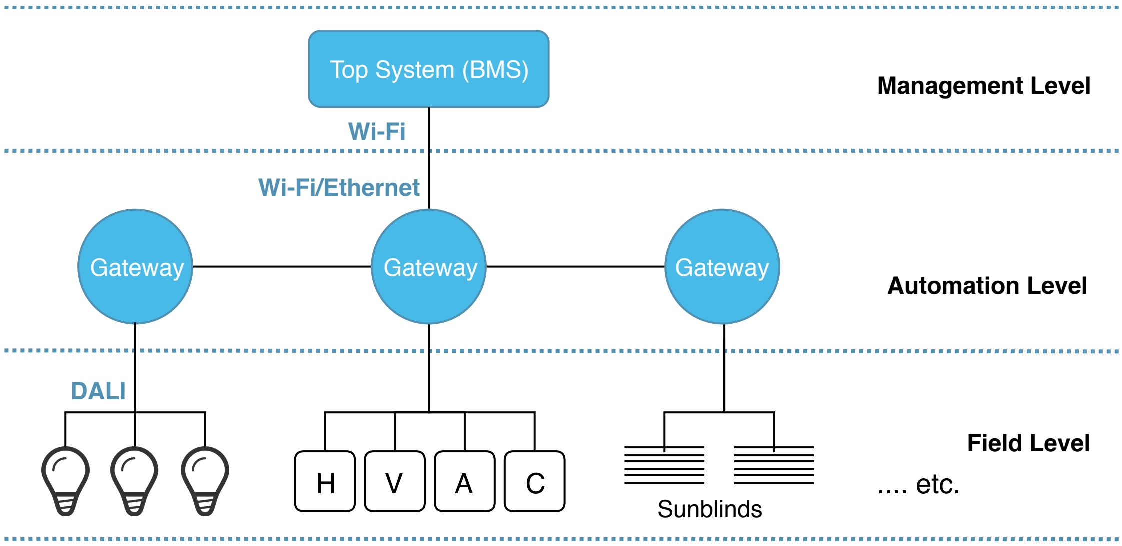

Figure F.2: Scenario 2: DALI, Wi-Fi/Ethernet and Wi-Fi

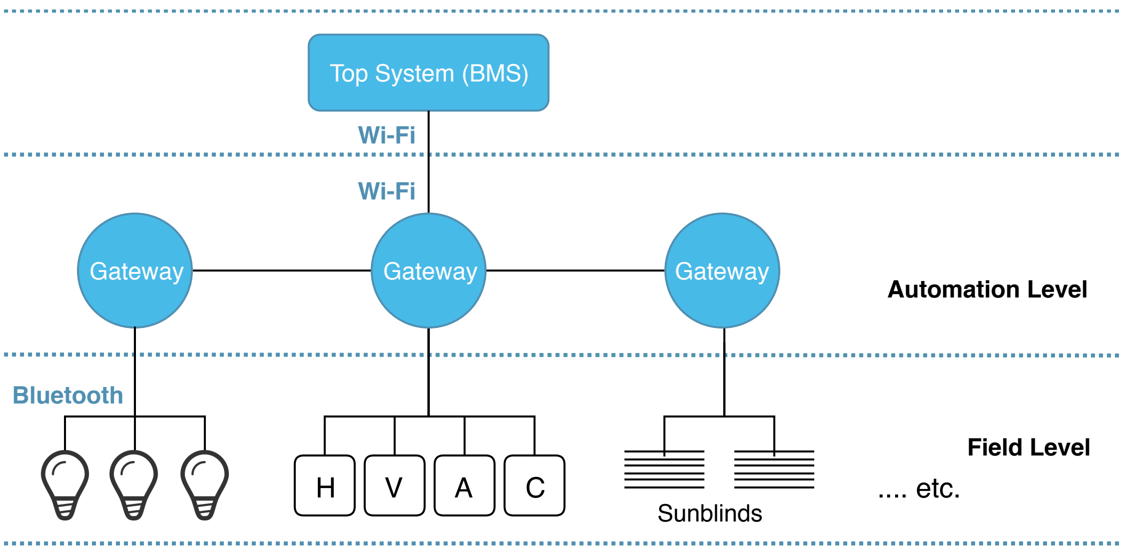

Figure F.3: Scenario 3: Bluetooth, Wi-Fi and Wi-Fi

Appendix G

Reference Project

The reference example project used in this thesis is a three-floor Norwegian office building of an over average size. Figure G.1 on the next page illustrates the various Glamox luminaires used in this reference example project. It is important to underline that this is not an actual project Glamox has delivered, only a reference example constructed especially for the purpose of this thesis. The reference example project does not include emergency and outdoor lighting. The following bullet point list summarizes the main characteristics:

- 150 office units. 60 closed offices and 90 cell offices. 4 kitchen. 10 meeting rooms. 8 toilet rooms.
- 3 luminaries in each closed office (1 of type C70-R G2, 1 of type C70-P and 1 of type "Ninety"). Built-in sensors in the roof luminaires.
- 2 luminaires in each cell office. 1 of type C70-P and 1 of type "Ovelo". Built-in sensors in the roof luminaires.
- 5 luminaires of type D70-R in each kitchen. 1 sensor in the entrance + daylight sensor.
- 4-10 luminaires of type C70-R in each meeting room. 1 sensor in the entrance to each meeting room + daylight sensor.
- A total of 4 luminaires in each toilet room. 2 of type A70-W365 over the mirrors and 1 of type D70-R in each toilet units (assumes 2 toilet units in each toilet room. 1 sensor in the main entrance to the toilet room.
- There exists a total of 100 luminaires in the hallways and stairways. Type C70-R G2, D70-R or similar.

Figure G.1: Illustration of the various luminaires (Glamox AS, 2018c)

Pictures found on the product web page of Glamox was used when making the figure above. Readers are directed to look up the given luminaire name on Glamox AS (2018c) for more information.

Appendix H

Cost-Benefit Analysis Explanation

In the CBA table on the next page of the appendix, the following abbreviations are used:
Glamox = G
Building responsible = BR
User = U
Society = S

Bluetooth is abbreviated as “BT” in the tables in three last pages of this appendix.

	DALI				Bluetooth Mesh				Comment to the post
Direct benefits	G	BR	U	S	G	BR	U	S	
Sales income	5	0	0	0	7	0	0	0	Income from the sale of the LMS (one-time income).
Subscription income	2	11	0	0	3	13	0	0	G: Data handling income. BR: Income from operating the LMS.
Indirect benefits									
Synergies to sale of other products	1	0	0	0	2	0	0	0	The LMS can have dynamic effects to other Glamox products.
Reduced energy usage	0	1	2	5	0	1	2	5	The LMS will lead to energy savings.
Increased Productivity	0	0	1	2	0	0	1	2	The LMS can increase productivity (= benefit).
Increased Comfort	0	0	1	1	0	0	1	1	The LMS can increase comfort (= more productive work).
Increased Flexibility	0	0	0	0	0	2	1	1	The BT LMS increases building flexibility.
Sum benefits	8	12	4	8	12	16	5	9	
Direct Costs									
Purchase/Material cost	2	5	0	0	3	7	0	0	Cost of buying the needed material.
Production cost	2	0	0	0	2	0	0	0	Glamox's cost of producing the LMS solution.
Installation cost	0	3	0	0	0	1	0	0	The cost of hiring installation contractors.
Operating cost	0	1	9	0	0	1	10	0	The aggregated cost for operating the LMS, inc. maintenance.
Indirect costs									
Initial and ongoing training	1	1	0	0	2	2	0	0	Ongoing training for DALI. Initial and ongoing training for BT.
Downtime revenue loss	1	1	2	2	2	2	3	3	Loss of income due to downtime. Gets an accumulating effect.
Support cost	1	1	3	0	1	1	5	0	Labor hours used to support the BR and the User.
Environmental degradation	0	0	1	3	0	0	0	1	Assumes that DALI is more material intensive.
Sum costs	7	12	15	5	10	14	18	4	
Bottom Line (Benefits-Costs)	**1**	**0**	**-11**	**3**	**2**	**2**	**-13**	**5**	

Row name in CBA	Glamox	Building responsible	User	Society
Sales income	Sales income for Glamox is equal to the purchase cost for the BR. BT can be sold at a higher price than DALI because of higher material cost and goodwill.	Not a benefit for the BR.	Not a benefit for the user.	Not a benefit for the society.
Subscription income	Lifetime income for handling and analyzing the data (most likely outsourced). Assumes more monitoring with BT.	What the BR earns on operating the LMS. Assumes more income from BT solution.	Not a benefit for the user.	Not a benefit for the society.
Synergies to sale of other products	One unit more for BT than for DALI because the BT solution is more likely to promote additional sales because of increased enthusiasm towards Glamox products.	Not a benefit for the BR.	Not a benefit for the user.	Not a benefit for the society.
Reduced energy usage	Not a benefit for Glamox.	The BR saves some energy in installing the LMS. Same for both protocols.	Assumes the user earns one unit more than the BR on reduced energy use.	Energy savings of 2 for the user leads to more savings for society because of accumulating effects (here environmental benefits is the most evident accumulating effect).
Increased Productivity	Not a benefit for Glamox.	Not a benefit for the BR.	The user will work faster due to the LMS which will benefit the organization where the LMS is installed.	Assumes one unit more than for the users. This is because increased productivity leads to more spare time which leads to more benefits for the society as whole.

Row name in CBA	**Glamox**	**Building responsible**	**User**	**Society**
Increased Comfort	Not a benefit for Glamox.	Not a benefit for the BR.	A functioning LMS with HCL features is proven to increase the comfort of the user - which leads to more productive work if used suitable.	Same as for the user. Do not influence other members of the society than the users of the building.
Increased Flexibility	Not a benefit for Glamox.	Only for BT. BT increases flexibility for the BR. Benefit in terms of more efficient use of the building.	Only for BT. Assumes that the users has a little lower benefit of increased flexibility than the BR (since the flexibility could possibly lead to new, threatening users).	Only for BT. Same as for the user. Do not influence other members of the society than the users of the building.
Purchase/ Material cost	BT got higher material cost than DALI at present. This is likely to even out when BT components gets more popular on the market.	Same as sales income for Glamox. Must at least cover the production/material cost plus the production cost for Glamox.	Not a cost for the user.	Not a cost for the society.
Production cost	Assumes about equal material and production cost. Same for both protocols.	Not a cost for the BR.	Not a cost for the user.	Not a cost for the society.
Installation cost	Usually the responsibility of the building responsible. Not a cost for Glamox.	DALI needs wiring in addition to the luminaires and BT only needs to install the luminaires (but can also have external sensors to install). Installing wires demands qualified electricians and takes more time to install.	Not a cost for the user.	Not a cost for the society
Operating cost	Glamox do not have a direct operating or maintenance cost of the luminaires.	Same for both protocols. A small amount.	Same as the total direct cost for the BR for DALI and one unit more for BT (assumes the BR can profit more from the BT solution).	Not a cost for the society.

Row name in CBA	**Glamox**	**Building responsible**	**User**	**Society**
Initial and ongoing training	Some training for implementing new functionalities with the DALI protocol/About the double amount of training required for the BT solution.	Assumes that the BR needs the same amount of training as Glamox.	Not a cost for the user.	Not a cost for the society.
Downtime revenue loss	Some downtime revenue loss for DALI and the double for BT (because of unstable mesh in the beginning and possible interference).	Same as Glamox.	Accumulates to one unit more of what the downtime revenue loss is for Glamox and the BR.	Same as for the user. The downtime revenue loss do not influence other members of the society than the users of the building.
Support cost	Glamox currently provides support to their Glamox Wireless system-customers. Assumed to continue with this. Same for both protocols.	Assumes that the BR uses the same as Glamox on support.	Same as the total indirect costs for the BR.	Not a cost for the society.
Environmental degradation	Not a cost for Glamox.	Not a cost for the BR.	Assumes that the users of the building lose income and/or goodwill when having a wired LMS because of the environmental issues. Not a cost for the BT solution.	Two units more on DALI than for the user. This is because using the wires will harm the society more than the users. Sat to 1 for the BT protocol because using material resources will always harm the environment.