UiO : Centre for Entrepreneurship
University of Oslo

Implementation of sensor technology in scaffolding – An application of technological brokering and smart product design

MSc in Innovation and Entrepreneurship

Christopher Ullrich
20.05.2016

HØGSKOLEN I BERGEN
BERGEN UNIVERSITY COLLEGE

Oppgavens tittel:	Implementation of sensor technology in scaffolding - An application of technological brokering and smart product design	**Levert dato:** 20.05.2016
Forfatter:	Christopher Ullrich	
Mastergrad:	Master of Science in Innovation, Entrepreneurship and Technology management	**Tall sider u/vedlegg:** 77
Veileder:	Jarle Aarstad Bjørnar Vasenden	**Tall sider m/vedlegg:** 79
Studieobjekt:	Sensor integration in scaffolding for increased safety.	
Metodevalg:	Qualitative method and use of textual data	

Sammendrag:

Collapsing scaffolds pose a constant danger in today’s construction industry and can result in serious injuries and substantial financial losses. To avoid the occurrence of such incidents on scaffold structures, a solution based on technological brokering between scaffolding and a wireless sensor network was evaluated on technological and market based feasibility.
Interviews revealed the wall anchoring of scaffolds as a weak spot, which frequently fails as a consequence of human errors. As a result, several sensor types where examined on their suitability as an automated early warning system for wall fixings.
Data from the interviews was analysed and suggested only a moderate marked feasibility, due to limited financial possibilities and modest innovation willingness within the scaffolding industry. The most promising design consists of either an accelerometer or strain gage, but low output signals, high noise levels and limited space make the system challenging and require extensive testing. Thus, the technological feasibility was found to be relatively low with several uncertainties when considering the requirements on simplicity, reliability, low time consumption and costs.

Stikkord for bibliotek: Scaffolding, sensor technology, technological brokering, smart products, push / pull strategies

Foreword

This master thesis is a final closure of the 2 years' Master program in Innovation and Entrepreneurship at the University of Oslo and in cooperation with Bergen university college.

My motivation for researching scaffold systems and sensor technology stems from my wish to practically use the knowledge I have gained throughout the master program. The idea was suggested by Inventas AS and immediately caught my interest. While theoretical fundaments are crucial for sufficient in depth understanding, actual values arise when theoretical foundations are applied to real world situations. For me, the topic seemed highly suitable for that purpose. The process of analyzing market and technological feasibility in an innovative context, resembles the various topics of my master program closely, with a practical orientation at the same time. Furthermore, my ambition was to provide useful and valuable input for Inventas AS and to prepare myself for a future career.

I wish to thank my supervisor Jarle Aarstad for his input and guidance which helped to point me in the right direction and properly structure my research. I also want to express my gratitude to Bjørnar Vasenden from Inventas AS for his extensive help, in particular for technical and business related topics. For me, it was a valuable experience to observe the processes and thoughts from a company's perspective on the way. ,
I am also very thankful for the help from all the respondents who made themselves available and without whom this research would not have been possible.

Table of Contents

1. Introduction 1

1.1. Outline 2

2. Theory 3

2.1. General structure 3

2.2. Innovation and technological brokering 5

2.3. Strategic choices of the innovation process; market push vs. market pull 6

2.4. Smart products, the new trend 9

2.5. Market considerations 11

2.6. Scaffolds 12

2.6.1. Regulations and procedures 14

2.6.2. Current dangers and potentials for improvement 15

2.7. Sensor technology 18

2.7.1. System set-up 21

2.7.2. Sensor technologies 24

3. Method 32

3.1. Textual data collection and general research design 32

3.2. Interviews 33

3.2.1. Interview structure 33

3.2.2. Sampling strategy and respondent selection 34

3.2.3. Practical set-up and execution of interviews 38

3.2.4. Interview guide 39

3.3. Data analysis of interviews and textual data 39

3.4. Follow up interviews 41

4. Results 42

4.1. Market feasibility 42

4.1.1. Interviews 42

4.2. Follow-up interviews 50

4.3. Technical feasibility 52

4.3.1. Conceptual analysis 52

5. Discussion 61

5.1. Innovation strategy and smart product design 61

5.2. Market feasibility 63

5.3. Technical feasibility 65

5.3.1. Sensor design 65

5.3.2. Sensor implementation 69

6. Conclusion 72

6.1. Implications, limitations and future research 73

7. References 74

8. Appendix 78

Table of Figures

Figure 1 - Eyescrew with rod connector 17
Figure 2 – Design tree, sensor type 19
Figure 3 - Practical considerations 20
Figure 4 - Traditional data acquisition system 22
Figure 5 - Stress - strain curve (Hibbeler, 2000a, p. 84) 27
Figure 6 - Wheatstone bridge and strain gage principal 28
Figure 7 - Requirements 52
Figure 8 - Plot of free vibrational acceleration 53
Figure 9 - Conceptual design, parts 54
Figure 10 - Conceptual design, assembly 55
Figure 11 - Conceptual design, sectional cut assembly 55
Figure 12 - Sensor distribution 57
Figure 13 - Wireless sensor node 58
Figure 14 - Trade-off table 71

Table of Equations

Equation 1 - Tensile and compressive force 18
Equation 2 - Vibrational Acceleration 26
Equation 3 - Strain 27
Equation 4 – Stress vs. strain 28
Equation 5 - Strain measurement 29

Table of Tables

Table 1 - Company type 36
Table 2 - List of respondents 37
Table 3 - Additional respondents 41
Table 4 – Results, market feasibility 48
Table 5 - Results, technological feasibility 59

1. Introduction

Innovative products and services are a critical success factor for many firms, particularly small and medium sized enterprises (SMEs) within a dynamic environment (Jones and Education, 2010, p. 89). Organisations need to adjust to the rapidly changing marked situation and find effective ways to gain competitive advantages. Creating new products by combining well understood technologies is one way through which such an advantage can be accomplished. Digitalization in particular, is a field where this phenomenon can be observed. Today's mobile devices and similar smart products which combine technologies from amongst other software applications and sensing technologies, are increasingly attractive products with a significant benefit for its customers.

Smart products are defined as physical hybrid products, combined and supplemented with sensing and telecommunication technologies (Mysen, u.å.). Furthermore, the method of combining different technologies is frequently referred to as *technological brokering* an implies (Arts and Veugelers, 2014, p. 1):

The innovation of new technologies by combining formerly disconnected but familiar technology components on the likehood of inventing more useful and breakthrough inventions.

Explained in its simplest form, technology brokering refers to the discipline of resource and technology recombination, where new innovations arise from the process of merging two or more existing technologies.

In this master thesis the innovation method of technological brokering of smart products is applied to the fields of sensor technology and scaffolding in close cooperation with Inventas AS, who came up with the idea of combining these two technologies. Inventas AS was founded through NTNU (Norges Naturvitenskapelige Universitet i Trondheim) and has established 6 regional offices in Norway since then. Their main specialization is the delivery of services within design and innovation (Inventas, u.å.).

Scaffolds are still fairly simple mechanical constructions, containing numerous perils and safety issues due to limited control mechanisms (Stangeland, 2016). A combination of incorrect use, lack of competence, misunderstandings and difficult weather conditions are seemingly factors which potentially lead to serious accidents and fatalities amongst constructions workers and passers-by (Østring, 2013). Simultaneously, recent sensor technology has become cheaper and more available. Thus, combining these two technologies might improve safety issues by providing additional warning systems. Although the oil industry has declined significantly the past year, there might be some market potential. As recently as in January this year, Statoil announced to invest 11 billion NOK on ISO services (Installation, scaffolds, surface treatment) throughout the next 15 years (Myrset et al., 2016).

However, an implementation of scaffolds equipped with sensor technology poses several challenges and uncertainties, as little is known about the general market demand and the technical limitations of sensors within the aforementioned field of application. This forms the baseline for the research question of this master thesis:

“ Is technological brokering of smart products in the fields of sensor technology and scaffolding feasible, when looking at technical and market based parameters? ”

In order to answer this question, general innovation procedures and smart product design are studied and translated into the field of interest; sensors and scaffolds. Furthermore, a market analysis is performed through qualitative interviews and related literature such that current challenges, opportunities and product requirements can be mapped. In order to properly conduct this research, general literature on innovations strategies is also studied. This includes primarily the use of technology push vs. market pull strategies. The former one refers to a new technology being pushed onto the market, while the latter one refers to technologies being developed in accordance with customer pre-existing needs (Ottosson, 2004, Brem and Voigt, 2009). Finally, the technical feasibility is validated by studying available sensor systems and their use for the scaffold industry, followed by a plausible conceptual design layout.

1.1. Outline

The relevant theory is covered in chapter 2. Background information on innovation strategies and smart products are studied and related to the subjects of scaffolds and sensor technology respectively. A market analysis is carried out through which the problems and needs of today’s scaffold industry are determined and the potential of sensor integrated scaffolds investigated. Chapter 3 gives a brief overview on how the research was conducted. The results will then be presented in chapter 4, followed by a discussion and conclusion in chapters 5 and 6 respectively. The conclusion will also include a recommendation for further research and discuss relevant limitations of this study.

2. Theory

In this chapter, the theory around innovation, smart products, scaffolding, sensor technology and a brief market analysis will be elaborated in detail. The thereof obtained information forms the theoretical foundation for the data collection process and data analysis.

2.1. General structure

As mentioned during the introduction this master thesis consists of a market and technical feasibility study. This is a typical process in engineering product development processes (Pahl and Beitz, 2013), which is shortly described below (Pahl and Beitz, 2013. p. 130):

- The first stage is referred to as the planning and task classification stage and consists typically of a market analysis, a product idea selection and a requirement mapping. Besides the establishment of requirements, a ranking on relevance is typically performed during this stage. However, the development process is rather dynamic such that requirements and aspects are likely to be changed and adjusted iteratively.
- The second stage consists of the conceptual design. During this stage a principal solution is made and typical challenges are identified. Furthermore, technical and economic aspects are evaluated. It is common practice to produce a preliminary layout with rough dimensioning and material choices. Since later stages are built on the principals which arise during the conceptual design phase, it is important to properly execute the processes of this stage. If several design options are made the least promising ones are eliminated during a critical feasibility evaluation.
- The embodiment design phase marks the third development stage. Existing layouts are refined and properly adjusted through several iterations, as more advantages and disadvantages become apparent. Also, at the end of this stage a more detailed verification process of technical and economical criteria's is performed. Ideas from others are frequently implemented to further improve the most promising design, which results in the definitive layout.
- The final stage is referred to as the detailed design stage. All subpart and single components are formed and dimensioned with the appropriate materials. Production is planned and costs estimated. Also product documentations are formed.

It should be noticed that this master thesis does not follow all aforementioned parameters, since it is not a pure product development, but rather a feasibility study considering market aspects and technological possibilities. Nevertheless, many steps performed will be closely related to a typical engineering product development process. The technological feasibility has to consider some relevant solutions and address the challenges with simplified models, principals and calculations if necessary. One or several possible layouts should be shown. Thus, the final stage will at most represent a rough conceptual design through which the general principal is illustrated. The market feasibility plays just as an important role. Through a relatively detailed market analysis, the challenges which the proposal is based on will be mapped carefully and the general market potential evaluated. Some theoretical aspects about innovation, strategies and smart products will also be relevant as they might provide helpful considerations and background information along the way. Finally, a conclusion will be made based on a critical assessment of the market feasibility and technological feasibility combined with input from general innovation strategies and smart product design. Thus, the purpose is to suggest whether or not further development is advisable based on findings and conclusive results.

The first part of the theory chapter provides a general understanding of innovations and its relevance for the industry. While several paths can result in the creation of new and innovative products, this master thesis focuses in particular on products which arise by combining already existing technology. Furthermore, the first part introduced considerations on innovation strategies and smart products and is together with the market research directly linked to the market feasibility aspect of the research questions. The second part of the theory chapter introduces construction scaffolds, typical usage and relevant regulations which functions as a transition between the market based and technological aspect. Furthermore sensor technology is introduced. Although the theories in part 2 are largely simplified they might be slightly more demanding to understand for the reader due to the introduction of some mathematical and physical principles. However they are important for estimating the technological feasibility.

2.2. Innovation and technological brokering

Innovation is a widely used term and has gained significant attention in our society. Various definitions have been established. Using the definition from Rogers (1998), p. 5, in its most simple form innovation can be defined as:

The application of new ideas to the products, processes or any other aspect of a firm's activity.

However, a precise definition is not as straightforward, as it depends on its application and interpretation of each individual. A somewhat more elaborated definition made by the Oslo Manual (Co-operation and Development, 1997, p. 31) is:

Technological product and process (TPP) innovations comprise implemented technologically new products and processes and significant technological improvements and processes.

In this definition products are referred to as goods and services, while the term "new products" denotes products which have been enhanced or upgraded significantly from existing ones. Furthermore the term technological process innovation is directly related to

New or significant improved productions methods, including methods of product delivery.

Evidence suggests a direct linkage between a company's performance and their involvement in innovative activities (Rao et al., 2001). Thus, a higher level of innovation intensity has a positive effect on sales growth, which is a major point of interest for most companies. Considering the market decline in the past years, partly due to decreasing oil prices, innovations in other fields might open new possibilities for the Norwegian industry. Furthermore, innovations are generally important for a nations market-development and wealth. Firstly, innovations are responsible for the creation of new goods and services which amongst other parameters potentially contributes to life quality enhancements of costumers, a rise in sales and the creation of jobs. Secondly, innovations and entrepreneurial activities potentially give birth to further innovation and new market opportunities (Sarasvathy and Venkataraman, 2011;, Walsh et al., 2002). Large breakthrough innovations can change the market rapidly, creating numerous possibilities for new products which further improve, refine and enhance the initial technology (Abernathy and Utterback, 1978).

Since the creation of new and improved products and services has such a significant value on society, this master thesis contributes to the validation of an innovative idea proposed by Inventas AS, where scaffoldings and sensors are being combined to a single product package.

There are many different factors of influence which promote the emergence of innovative solutions. It is often argued that new knowledge plays an important role in the process and that spatial proximity might have benefits for knowledge exchange (Tödtling et al., 2009). Since a simple float of codified and tacit knowledge create a crucial linkage to new information, a network is beneficial. While codified knowledge is less sensitive to distances, tacit knowledge requires a high degree of personal interaction (Asheim and Gertler, 2005). It seems logical that the transfer of knowledge can result in different applications of similar technologies. A solution from one company might be beneficial for the customers of another company, which tailors the same idea into new concepts and combinations (Hargadon and Sutton, 1997, p. 716). Since these innovations are based on existing ideas combined with other concepts, new innovative products and solutions can arise. More specifically, a terminology for the aforementioned type of innovation is technological brokering, where products are created by a connection of understood technologies from one sector with the ones from another sector (Howells, 2006;, Arts and Veugelers, 2014). Innovation through technological brokering is the underlying process of this master thesis. Existing concepts from the sensor industry are applied and customized for customers in the construction industry. A scaffold system combined with different measurement devices that mostly operate autonomously is a recombination of independently established technologies. It seems technological brokering might have advantages. Since the components have been used extensively in earlier applications, a lot of information of each component is available. Thus, a recombination and reuse of these different technologies is easier to predict compared to innovations that are based on unproven concepts (Arts and Veugelers, 2014). Research suggest that technological brokering might be beneficial for breakthrough inventions (Arts and Veugelers, 2014). At the same time it appears like the chance of failure is reduced and average usefulness improved as long as the result is a truly new technology.

2.3. Strategic choices of the innovation process; market push vs. market pull

Innovations usually originate from either one of two main driving factors; technology push or market pull, but can also result from a combination of these.

Technology push is an innovation strategy where products are developed from new insights and research discoveries frequently seen in the fields of medicine, physics and biology. These discoveries construct in particular a baseline for new products, which are then pushed onto the market by inducing a market need (Ottosson, 2004). Thus, the technology push strategy focuses more on pushing R&D related finding onto the market, without conducting a detailed market analysis of customer needs throughout the process. Since technology push originates from more intensive R&D related activities it often plays an important role in the development of radical product innovations, which are significant new or breakthrough innovations currently unknown to the general market (McDermott and O'Connor, 2002). Market pull strategy uses a different pattern. Here the product creation is mainly based on the fulfilment of insufficiently covered customer needs (Brem and Voigt, 2009). Therefore a more detailed market research is usually performed initially, such that specific customer needs and wishes can be mapped and included in the product development process. Furthermore, market push as a strategy is frequently used for incremental innovations, which are characterized as less significant innovations, with customer requested improvements or extensions of current products and services (McDermott and O'Connor, 2002).

Earlier research also indicates a relation between the type of company, the produced technology and the preferred market strategy (Walsh et al., 2002). New and smaller firms seem to prefer the introduction of disruptive technologies on the market and primarily use the market pull strategy to achieve this. Disruptive technologies refer to technologies which require significant adoption by the customer and changes to current manufacturing and handling procedures (Walsh et al., 2002). Since new firms typically have a smaller customer base, they are less effected by customer needs which frequently requires improvements on a firm’s product series. Hence, they have more freedom to focus on disruptive technologies. Although market pull is the preferred strategy, many small and new firms also apply technology push. In their early stage they have not yet established strategic advantage through satisfied customers in the same degree as larger firms and have less to lose by pushing technologies onto the market. Furthermore, they have not developed the same amount of firm related core-competences yet. Thus, their core-competence to a higher degree originates from the outside environment of the firm, which more frequently yields disruptive technologies (Walsh et al., 2002). Introducing disruptive innovations to the market yields a higher risk since the time to market is rather unpredictable. This gives rise to financial uncertainties and complex planning practices. Furthermore, the changes in handling routines and adoptions required by the new technology increases the chances of market and customer resistance. However, disruptive technologies frequently lead to great opportunities in the form of strategic market advantages and higher revenue (Walsh et al., 2002). The same research also found that more established firms are more inclined to use market pull strategies, and prefer evolutionary technologies, which are more incrementally evolving technologies that do not alter current manufacturing and handling procedure (Walsh et al., 2002). Often these firms already have a faithful customer group, which has specific needs and requirements. Introducing disruptive technologies can disturb the firm-customer relation and lead to customer resistance. In addition, established firms have frequently developed certain core competence inside the firm on which they base their innovations. This will more likely lead to the development of incremental and evolutionary technologies with gradual improvements and improved efficiency as a result. In case of the technology push strategy for larger and more established firms, the general advice is to move the innovation to a separate department (for example R&D) or give the responsibility to independent organisations. For small/new firms, the technology push strategy becomes a responsibility of everyone. (Walsh et al., 2002)

Another way one could look at the type of product innovation is the degree of continuity (Veryzer, 1998). Thus, products are characterized by the degree of product capability and technological capability. The degree of product capability describes how enhanced the benefits of a new product are perceived by the customer. The degree of technological capability refers to the degree which the new products' functions exceed present capabilities (Veryzer, 1998). Using this model, an innovation with little product and technological capabilities falls into the category of continuous technology. A continuous technology shares a similarity with evolutionary innovations. On the other hand, products which resemble a high degree of both technological and product capabilities are considered to be discontinuous or radical. Furthermore, there are two more options, where a product significantly enhances either technological or product capabilities, while the other one remains largely unchanged. According to (Veryzer, 1998), continuous innovations tend to follow a rather structured scheme where market opportunities and customer needs are evaluated against the concept. A discontinuous product development process on the other hand is to a larger degree technology driven. While customer input is still valuable in particular for the evaluation of customer needs, it is harder to obtain reliable customer data in general, as the presented technology is harder to understand for customer groups. Furthermore, the development time for these products is typically quite high which implies a more notable absence from the market during some development stages. Put differently, customer orientation is still important for the early stages (customer need and product path identification) and the final stages (detailed specifications etc.), while a large portion of the intermediate phase is rather technology driven with little input from customers with clear mark push parameters (Veryzer, 1998). A major characteristic of discontinuous innovations is the general difficulty to keep the process highly structured, which implies a high degree of technological and market based uncertainty. This seems to be identical to the findings of Walsh et al. (2002)

Other studies stress the general importance of customer based orientation. An extensive study of successful innovations referred to by Cooper (1983), stated that only 21% of the technology push based innovation were successful, while the remaining success stories were market pull driven. It should be noticed, that these findings are relatively old with limited details about the type of products and companies. Purely push and pull strategies can appear to be very limited and linear models compared to the complexity of innovation processes. Hence, it might be much more realistic to look at innovative processes as dynamic (Tidd, 2006). Far more interactive models based on network linkages and continuous innovations seem to be a more modern approach to innovation strategies. A generation based model on innovations is presented by Rothwell (1994). According to the aforementioned innovation model, market push and technology pull are the first two generations of innovative strategies widely used in the 50's and 60's. Without going too much into detail on the different models, the modern strategies, in particular the 5th generation of innovation focuses a lot on systems integration with networking, interfirm integration and flexible customized responses.

It appears that innovation strategies are complex and situational dependent on specific circumstances. However, dynamic models are more realistic compared to the more conservative push/pull strategies.

2.4. Smart products, the new trend

As mentioned in the innovation section, the creation of new and innovative products is of significant importance for society and the development of better technologies. Combining sensors and scaffolding will hopefully result in scaffolds, which to a larger degree are based on automation compared to current designs and which generally can be defined as "smarter" constructions. This requires some information on the application of smart products which is a modern technological trend, closely related to the disciplines of ergonomics and industrial design (Rijsdijk and Hultink, 2009).

The idea is that scaffolds with integrated sensors will become smarter and safer than currently provided solutions. The term "smart scaffolding" will be used more extensively in the following chapters and denotes scaffolds that are equipped with various sensors for safety improvement purposes.

In simple form, smart products are physical products which are combined with various sensing and telecommunication technology (Mysen, u.å.). The supplementation of various information technology (IT), enabling these products to collect and process data in a way which allows a certain degree of individual thinking and autonomous operation (Rijsdijk and Hultink, 2009). According to Rijsdijk and Hultink (2009) one important deliberation concerning smart products is their perception by the customers. Evidence suggests that customers have different opinions to different types of smartness (Rijsdijk and Hultink, 2009). In order for a product to be classified as smart it needs to contain at least one of these smartness dimensions which are autonomy, adaptability, reactivity, multi-functionality, ability to cooperate, humanlike interaction and personality. An additional requirement for smart products is the inclusion of information technology.

Autonomy is the degree to which the product is able to operate independently, without the involvement of the user. Adaptability refers to the ability to process data from the environment and to adjust its functionality accordingly, such that better performances are achieved. Increased reactivity and multi-functionality enable the product to react to changes induced by the environment and the option to fulfill several customer needs respectively. Ability to cooperation is the possibility of a product to function in module like set-ups, where a form of communication exists between several units. The final two smartness dimensions, humanlike interaction and personality, are product traits which enables natural communication with the user and the ability to show signs of a real character that the user can identify himself to. The research conducted by Rijsdijk and Hultink (2009) shows that a higher degree of smartness in the fields of autonomy, adaptability and reactivity is often associated with a higher level of risk, which amongst other things can be grouped into financial risk and performance risk. Also, a majority of customers might conceive smarter products with the aforementioned characteristics as advantageous. The term *advantage* refers to the product being superior compared to the task it substitutes. Products which replace cognitive functions are furthermore received as less complex, while the opposite is seemingly true for product executing physical tasks. Increased reactivity is related to a higher perceived advantage and better compatibility as long as the reactive function does not involve the user to a large extent. Also a certain degree of multi-functionality is advantageous, there is a limit on how much functions smart products should have. An extensive number of functions increases the perceived complexibility and risk association. Thus, a high degree of functionality might have a negative impact on customer satisfaction. It seems like simplicity is more appreciated.

This fact is also confirmed by other research. According to Buurman (1997), a user-centred design is crucial for satisfaction. Products with many functions are often considered complex and disadvantageous, especially for the casual user or for products having a poor interface. In this perspective it seems like functionality is only desirable as long as it does not compromise the “ease of use” parameter to a large degree (Mühlhäuser, 2007). Thus multi-functionality has to be realised with extensive customer involvement. Cooperation, the final smartness dimension seems to be perceived with mixed feelings (Rijsdijk and Hultink, 2009). For certain product categories it seemed like users do not appreciate cooperation between different modules, as it increases risk and complexity. For other products, especially the ones where cooperative functions are expected, the ability to cooperate was perceived as advantageous.

2.5. Market considerations

For the market feasibility, customer needs and pains are examined. If it turns out that customers are facing a lot of difficulties during scaffold related work it would open opportunities for solutions. In other words, job related pains create opportunities for pain relievers (Osterwalder et al., 2015). Thus, the most important aspect of the market feasibility study is to find current safety issues and problems, followed by further in depth analysis on the pain with highest relevance. In addition information about economic aspects is investigated. The innovation has to be economical viable and create revenue. This cannot be guaranteed by a few interviews but a market analysis at this stage should give rough indications on the economic potential (Pahl and Beitz, 2013, p. 131). Another point of interest for the conceptual design phase is the mapping of customer requirements, which has a significant influence on product feasibility and product design.

Some literature might suggest a relatively low market potential. For instance, global analysis from Deloittes examined how significant different industries might be affected by technological change in the coming years (KLAUS BØRRINGBO and BRAATHEN, 2016). As expected, the IT industry seems to experience the highest innovation activity within a short timeframe. The construction industry is lagging behind. Although new technologies might appear within the next 2-3 years, the changes are expected to be low for the construction and scaffolding industry. Although these results are a good indicator more reliable information on the actual market interest will be provided through interviews with potential customers.

This completes part 1 of the theory. It seems like the general benefits of innovative activity are high. The role it plays for a company’s survival and the development of the surrounding market should be a motivator to engage in the creation of new technologies. In particular innovations through technological brokering, which is the strategy applied in this master thesis, appears to be of great potential by combining reduced risk and increased usefulness with new product development. Considerations related to disruptive and evolutionary technologies are important for the market aspect. However, more attention should be given to dynamic strategies, as market pull and technology push seem to be outdated. Innovations related to smart products seem to have a great potential but care should be taken throughout the development process, as smart product characteristics seem to have important influence on the user's perception.

2.6. Scaffolds

The second part of the theory chapter focuses on scaffolding structures and sensors. Scaffold related information is important both for the market aspects and the smart scaffold design process. Thus, the scaffold section is a transition between the market based and technology based part of the research questions, as it creates a bridge between technological feasibility and market feasibility. The sensor subchapter on the other hand will mostly relate to the technological aspect of the research. Since several results are needed from the conducted interviews, some statements might refer to the method, result and discussion section. Therefore, the interviews were performed and analysed ahead of this part and aspects of the following sections are partly based on these results and discussions. However, in these cases notice will be given.

Scaffolds can be defined as (Wang et al., 2012, p.1):

"A temporary structure used to support people and material during construction or maintenance of buildings and other large structures"

Although definitions might vary somewhat depending on the source and specific application, the main idea and terming is largely identical to the aforementioned definition. According to the interviews performed in this master thesis, the scaffolding industry has only seen few changes and innovations the past years (Respondent 1, 3, 5 and 6; Interviews). The general concept and main idea has been unaltered throughout the last decades. However, according to the same respondents, important changes have been applied to the material selection. Today, aluminium is mostly used compared to the heavy steel structures many years ago. However, in other countries steel is still more used than in Norway (respondent 5 and 6; Interviews). From the interviews it seems like Norway has been a leading country in the development of

aluminium scaffolding, particular due to investment willingness from the petroleum sector. The advantage of aluminium scaffolds is its reduction in weight (about 50% lighter) which potentially reduces injuries during set-up phase, working efficiency and general wellbeing without a significant compromise in strength (Solideq, u.å.;, QuickAlly, u.å.).
Also, scaffolding systems are divided into different classifications according to NS-EN12811 which is directly related to its load capacity and area of use, see below (Solideq, 2014;, DeltaSystem, 2012);

- Class 1 is the lowest scaffold class only meant for light work and tools. Examples are inspections. No storage is allowed on class 1 scaffolds. The average distributed load is 750 N/m^2.
- Class 2 allows the storage of some working tools and materials which are meant to be used in the near future. Examples of performed tasks are cleaning, easy carpenter work, electrical work etc. An average distributed load of 1.5 kN/m^2 is allowed or a concentrated weight of 150kg on a (50x50) cm area
- Class 3 has a slightly higher load tolerance of 2 kN/m^2 average distributed load and with a (50x50) cm concentrated load of 1.5 kN However, in terms of usage the types of permitted work are similar to class 2 structures and include pipe fitting work, carpenter work, isolation etc. Class 3 scaffold are frequently used on land based construction work.
- Class 4 scaffolds are suitable for heavier usage. Up to 500kg can be stored per square meter. The general load tolerance is specified to 3 kN/m^2 with a (50x50) cm concentrated force of 3 kN. Typical jobs performed on class 4 scaffolds include masonry and concrete elements.
- Class 5 is very similar to class 4 in terms of use. It finds its purpose in large industrial applications. An extra storage of up to 750 kg is possible, with an average distributed load of 4.5 kN/m^2 and the same concentrated force as class 4 scaffolding.
- Class 6 is the highest rated class. Many manufacturers require specific calculation if these scaffold systems are used. The allowed storage weight amounts to 1000 kg, with an average distributed load of 6 kN and concentrated forces equal to classes 4 and 5.

In Norway two main types of scaffolds are commonly used in the construction industry; Rammestillas, which is a typical light facade scaffold and Spirstillas, a form of heavier modular scaffold (Byggsystemer, u.å.). The former one is typically made out of aluminium and used within classes 2-3, while the latter one is usually applied for heavier industrial applications within classes 4-6 (Stillasentreprenørenes Forening, 2013, Deltasystem, u.å.). Heavy scaffolds are available in steel or aluminium from most manufacturers. However, the area of use can vary to some degree for both types. Especially spirstillas finds its application in many fields, ranging from shipbuilding and bridge construction to aircraft manufacturing (Proffstillas, u.å.). On offshore platforms hanging scaffolds are frequently used. Furthermore, rolling scaffold exist which are extremely portable due to their wheels at the bottom.

In this master thesis light Rammestillaser and heavy Spirstillaser (classes 3-5) in facade related applications are used as a baseline. This decision is based on the interview results (Table 4 – Results), where the wall fixings were found to be the most practical and useful application of a potential sensor based product.

2.6.1. Regulations and procedures

In this section a short description of the most relevant and important regulations is given. Some important changes have become effective since the 1st of January 2016. While special training requirements were applicable to scaffold systems with the highest floor being more than 5 meters, this requirement has been reduced to 2 meters and higher (Lovdata kap. 17 Arbeid i høyden, 2016). According to § 17-2 to § 17-5 the following detailed requirements apply (Lovdata kap. 17 Arbeid i høyden, 2016):

- §17-2 Independent work related to assembling, disassembling, change and control of scaffold systems, requires the concerning person to fulfill a theoretical and practical training of 7.5 hours respectively, under the supervision of a qualified person.
- §17-3 For the execution of independent work on the assembling, disassembling and change of scaffolds with a floor height of 5-9 metres, a 15 hour theoretical and 15 hour practical course has to be completed under the supervision of a qualified person.
- §17-4 For assembly, disassembly and change related work on scaffold systems exceeding a height of 9 metres, a supervised course by a qualified person has to be finished. The course needs to consists of 36 hour theoretical and 72 hour practical work. In addition, practical experience with scaffold systems for at least 6 months has to be documented.
- §17-5 The employer has to make sure that all employees who are using the scaffold as a working platform have received sufficient training in the assembly, disassembly and use of the scaffold structure. This is also a new regulation since 1st of January 2016.

Some other regulations which might be of relevance for this master thesis are related to inspections of scaffolding structures. The §17-9 and §17-10 (Lovdata kap. 17 Arbeid i høyden, 2016) state that scaffold have to be checked before use, after a week without use and whenever certain conditions might have contributed to changes in stability and strength. For instance after storms. Furthermore, a report of these checks has to be written. Next to the person in charge of the inspection, technical information and found deficiencies have to be included and signed. There are also certain regulation related to the anchoring of scaffolding. §17-18 (Lovdata kap. 17 Arbeid i høyden, 2016), states that the anchoring has to be performed according to the manual or specific calculations. A safety margin of 20% has to be added to the capability of resisting tensile (pulling, stretch) and compressive (compression, pushing) forces.

The aforementioned regulations are the most relevant for this master thesis, since they provide some technical information and potential competitors or resistance factors to the presented smart scaffold technology.

2.6.2. Current dangers and potentials for improvement

In this section frequently occurring dangers in the scaffold industry are investigated to give a better picture about current challenges. According to Stabenfelt (2015) the number of human injuries on scaffolds within the petroleum industry has fluctuated between 9 to 12 per year, with a slight increase from 2011 to 2014. In general 149 incidents have been registered which caused the plunge of items or parts. There are two dominant factors which contributed to most of these situations. About 25% were due to outer conditions, while close to 75% were caused by human activity. More than 50% of the human caused plunge incidents were latent, meaning that the effect did not occur immediately. Of all the latent human caused incidents, about 70% were caused by poor securing measures. While the petroleum industry might not be representative for this master thesis, it shows that even in the oil industry incidents are happening mainly due to human errors. Referring to the interviews conducted (respondent 3 and 6; Interviews), it seems like the petroleum industry has higher safety standards compared to the construction industry. Thus, it can be assumed that the number of unwanted situations is a lot higher for the construction industry.

Looking at some past incidents it becomes clear that potential for improvement exists. In July 2014 a scaffold collapsed in Tromsø centrum (Østring, 2013). The 4 meter high scaffold was in the process of being assembled while the incident occurred. A passerby almost got hit but the scaffold smashed down on a taxi instead. Missing wall fixings were the cause of the problem. Another example of scaffold tipping over in a densely populated area happened in march 2013, where a scaffold was falling over towards a neighbouring house in Sandviken (Valaker, 2013). Although the cause is not stated, it seems obvious that the problem was caused by wall fix failure. In April 2015 a 7 story large scaffolding collapsed in Sirisskjær for unknown reasons. Indications hinted in the direction of poor fixation to the wall as a possible cause (Nedrebø, 2015). Many other similar accidents have been reported throughout the past years. It seems like wall fixings might be a weak spot which causes scaffolds to fall over, especially under the presence of strong winds.

Dangers due to strong winds and scaffold tarpaulins or sheets are also confirmed by Wang et al. (2012). Sheets or tarpaulins are frequently used to reduce environmental and noise influences. In particular they protect workers from various weather conditions and prevent items from falling down (Malthus, 2016). Also, the scaffolding arrangement and building opening ratio have influence on the wind forces acting (Wang et al., 2012). The opening ratio denotes how many open areas a building under construction has compared to the total building area. Thus, a higher opening ratio describes a large amount of open areas, which might indicate an early phase of the construction process. From windtunnel testing it seems like the positive local windforce coefficient increases significant as the opening ratio decreases for scaffold arrangements which are enclosing the building on 1 or 2 of its sides. In other words, for non-circumference scaffold arrangements positive local windforce coefficients are decreasing as more open area's the building under construction has. For negative wind coefficients the effects are smaller. Globally, when looking at the whole scaffold it was also shown that peak forces are occurring on the top or side edges of the scaffolding structure (Wang et al., 2012). These tests were performed with tarpaulins of 0% porosity, meaning that absolutely no wind could pass through. Furthermore, the results showed that one sided scaffold structures or those only encompassing 2 sides are subjected to larger positive or negative windforce pressures then fully surrounding scaffold systems. Also, windpressures on the inner side of the scaffolding are more relevant when using sheets than the pressures on the outer surface. An interesting fact is that the aerodynamic wind force coefficient for the entire scaffolding by BS EN 12811 (British Standards Institution, 2003) was set to 1.3 for perpendicular wind directions, while the windtunnel tests gave values up to 1.7. Also the recommendations from SCEA (scaffolding and construction equipment association of Japan 1999) underestimated wind force coefficients. These results might hint in the direction that forces on sheeted scaffolding are underestimated for some geometries at certain portions of the scaffold (side and top edges).

According to the industrial service provider Safway there are many different problems which can be caused by wind (Safway Service, 2010). In particular for sheeted scaffolds wind can cause direct pressure forces but also suction forces on the opposing side, which are pushing the structure away from the wall. Even lift forces can cause planking on the scaffold system to fly away. The importance of tying the scaffold properly is specifically mentioned. Generally scaffolds are designed to withstand forces in the vertical direction. However, as windforces are present, horizontal forces and moment can be quite significant.

Since the interviews revealed wall mountings to be a major challenge, some more details will be provided on these. A typical wall fixing consists of several parts. Firstly an eyescrew or eyebolt is mounted into the wall. For wooden walls a regular eyescrew is used. For application involving concrete walls and eyebolt combined with a wall plug is installed. The dimension of the eyescrew/eyebolt seem to vary according to the applications. Fischer Norge AS uses mostly a thread diameter of 8, 10 or 12 mm, while the eyescrew length varies from 50 mm to 350 mm (Fischernorge, u.å.). The used material for the eyebolts/eyescrews is steel with quality 4.6 or 4.8 with a galvanised zinc coding. The coding prevents the steel from rusting. A rough sketch of an eyescrew and connector rod has been created in SolidWorks and is shown below (Figure 1 - Eyescrew with rod connector):

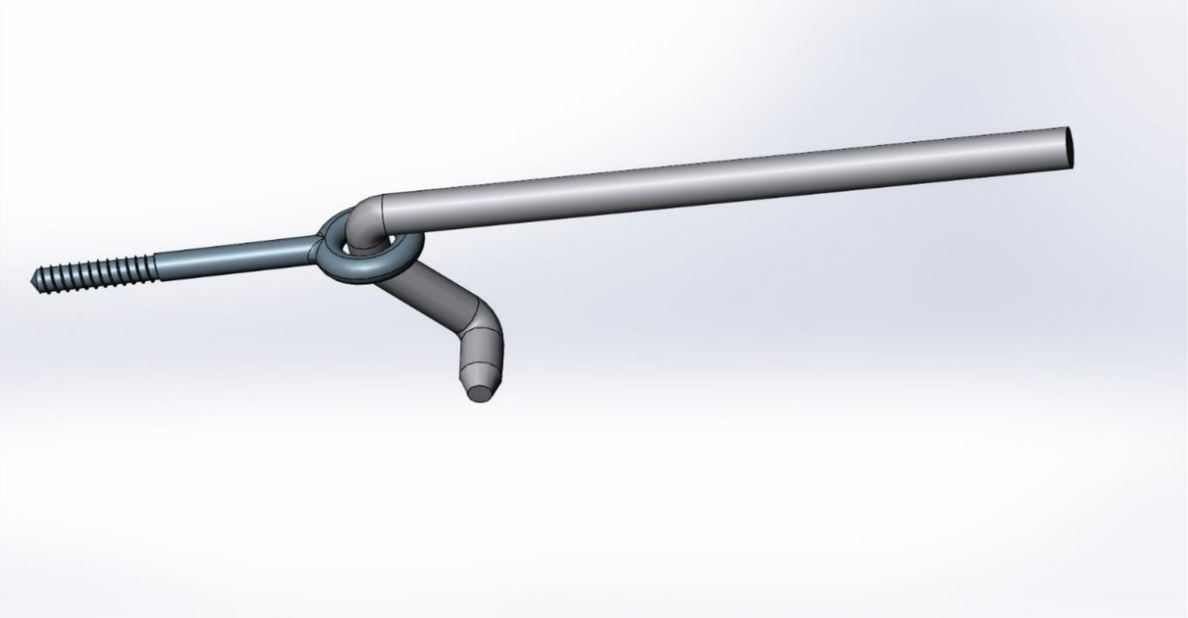


Figure 1 - Eyescrew with rod connector

It should be noticed that many variants and shapes exist for the connector rod. Also the eyescrew can have different dimensions depending on its specific application.
For uniaxial loads (loads along one axis) the maximum force for eyescrews and eyebolts can be estimated by (Equation 1 - Tensile and compressive force) derived from (Hibbeler, 2013):

$$F = \sigma_{max} * \pi r^2$$

Equation 1 - Tensile and compressive force

Thus, the force (F) can be found with the stress properties of the material (σ_{max}) and the radius of the bolt (r). Using an eyebolt with a thread diameter of 8 mm stress values of 240 MPa and 400MPa (US-BLM, 1990), the required force for yield and failure are about 12 kN and 20 kN respectively. In other words, at about 12 kN the bolt would start to deform permanently (yield), while about 20 kN of force are required to break the eyebolt (failure).

According to Aluscaf and Alby's monteringsanvisning (Solideq, 2014, Alby Byggmester, u.å.), the wall anchorage has to handle a minimum of 0.8 kN. Respondent 5 (Interviews) mentioned a pull force requirement of 108 kg, which is about 1080 N. Also Arbeidstilsynet claims a minimum pull force of 80 kg with a safety factor of 20%, which implies a anchoring requirement of just below 1 kN in pull force (Oversikt over endringer fra 1.1.2016 - Arbeid i høyden, 2016).

All the aforementioned values are far below the calculated ones, which makes a failure due to uniaxial load in tension highly unlikely from a theoretical perspective.
It seems more realistic that the anchoring system would fail due to the eyescrew or eyebolt being ripped out of the wall due to incorrect installation or when tractive force capabilities are not verified during set-up.

2.7. Sensor technology

In this section some background information on sensor technology is provided. The theory and information found throughout this section will be mainly used to answer the technical feasibility of the research question. Furthermore, it will be used as the background for a principal solution.

According to Storey (2009), p. 203, sensors and actuators are frequently referred to as transducers, which are devices capable of converting physical quantities into other quantities. The difference between a sensor and an actuator is the conversion direction. While a sensor uses physical quantities as an input and electrical signals as an output, actuators take electrical input signals and converts these into physical phenomena (Wilson, 2004, p. 1).

Using relevant information from the previous sections and the conducted interviews the emphasis is put on sensor technology for scaffold anchoring, as wall fixings seemingly are the cause for most undesirable incidents. Since there are many approaches which could potentially result in a solution, a rough design tree is made initially Figure 2 – Design tree, sensor type)

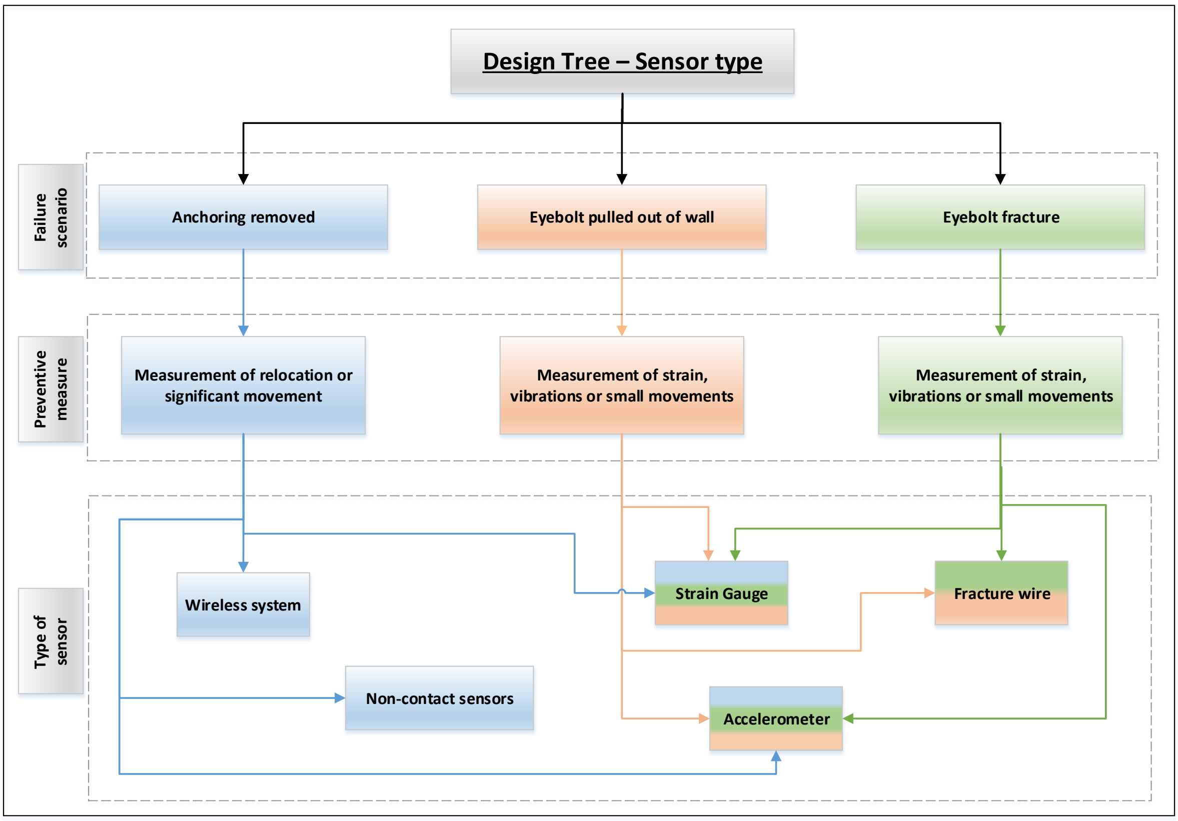


Figure 2 – Design tree, sensor type

In the first row of Figure 2 – Design tree, sensor type), the most relevant causes for failure and failure modes on scaffold anchoring are listed.

- The first cause is either related to the removal of too many load carrying wall anchors or an incorrect installation after removal, which results in reduced load carrying capacities. If the wall anchor is installed incorrectly it might fail under lower loads. If several anchors are removed, the stress on the remaining anchors will be higher.
- The first failure mode is related to incident caused by the whole eyebolt/eyescrew being pulled out of the wall by force.
- The second failure modes is a direct fracture of the eyescrew, most likely in the area around the eyescrew head.

For each failure mode a preventive measurement method is suggested and a possible idea of types of sensors provided. It should be noted that all failures are assumed to be caused by incorrectly mounted, faulty or removed anchors. Hence for both failure modes a solution is suggested. General notification of removed and repositioned sensors might be provided by either a wireless communication system or non-contact sensors. For both failure modes, accelerometers, strain gages and fracture wire systems seem to be appropriate solutions.

After collecting the most feasible sensor components a few practical consideration have to be made. Due to the limited amount of time, these will not be elaborated in detail. However, a short discussion about recommended choices are included (Figure 3 - Practical considerations)

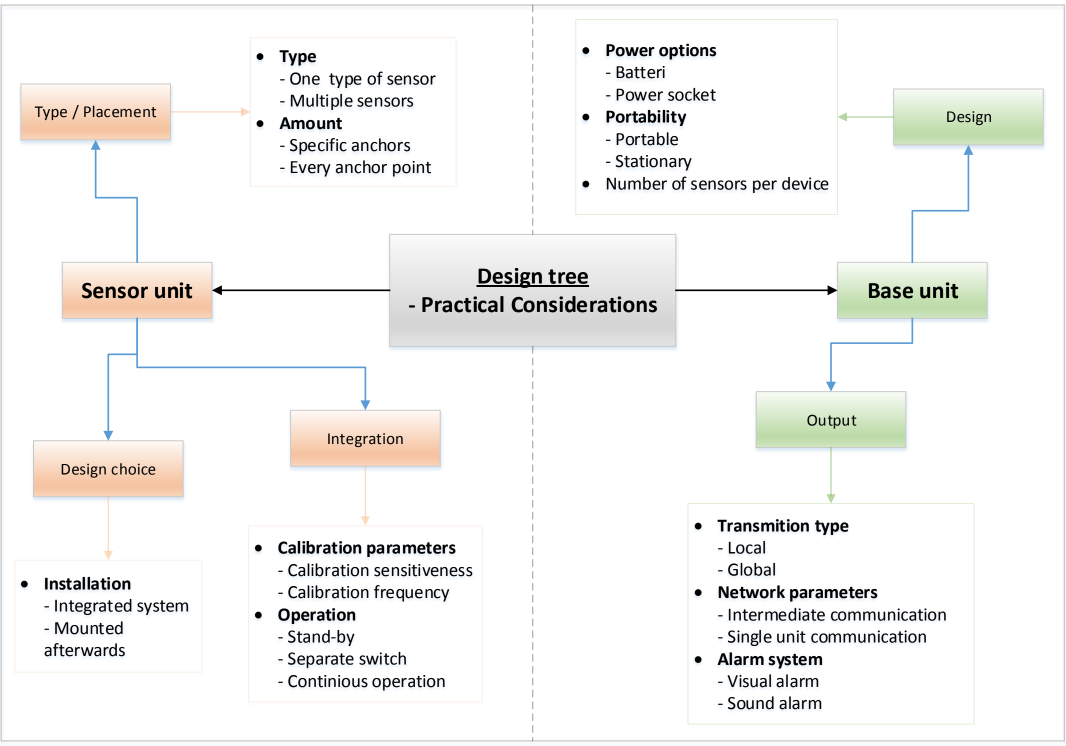


Figure 3 - Practical considerations

For the sensor unit, the type of sensor and number of used sensors has to be chosen. Potentially, one single or multiple sensor could be used. Furthermore sensors might have to be applied either on every wall anchor or only the critical loaded ones. The sensor unit might be produced as a finished and integrated solution or as an individual part where which is subsequently installed by the customer after scaffolding set-up. The final important sensor related considerations are calibration practices and operation principals. Some sensors require frequent calibration as environmental factors change while others only need to be adjusted after installation. Since the sensors are battery driven they should consume as little power as possible, such that a reasonable battery service life is achieved. However, this can also be influenced by operational parameters. If the sensor unit is operating continuously, larger power usage is expected compared to sensor that have an integrated sleep-mode function or can be switched off manually.

Also the base unit has to undergo many design specific considerations. Portability and maximum range for safe signal reception have to be practical. A battery powered base unit would be more portable, but might be more expensive. Since an unknown amount of sensor might be used, it is also important to consider the number of sensor that are connected to one base unit. Finally, output decision have to be made. In case of an irregularity the customer has to receive a notice. This could be achieved through visual or sound based alarm system. Different lights could also indicate different states like a low battery warning. Notifications might only be transmitted locally or sent to any device via app or mail, regardless of the customers location.

2.7.1. System set-up

This section describes the typical sensor system set-up and illustrated how physical phenomenon’s are translate to useful output. Furthermore, a short overview over wireless network sensing is given.

A classical sensor interface or data acquisition system consist of several components which create a measurement chain. In engineering context a system refers to a closed volume with known input and output parameters (Storey, 2009, p. 195). A simplified figure referring to (Reverter, 2012, Wilson, 2004, p. 577, Storey, 2009) is shown in Figure 4 - Traditional data acquisition system)

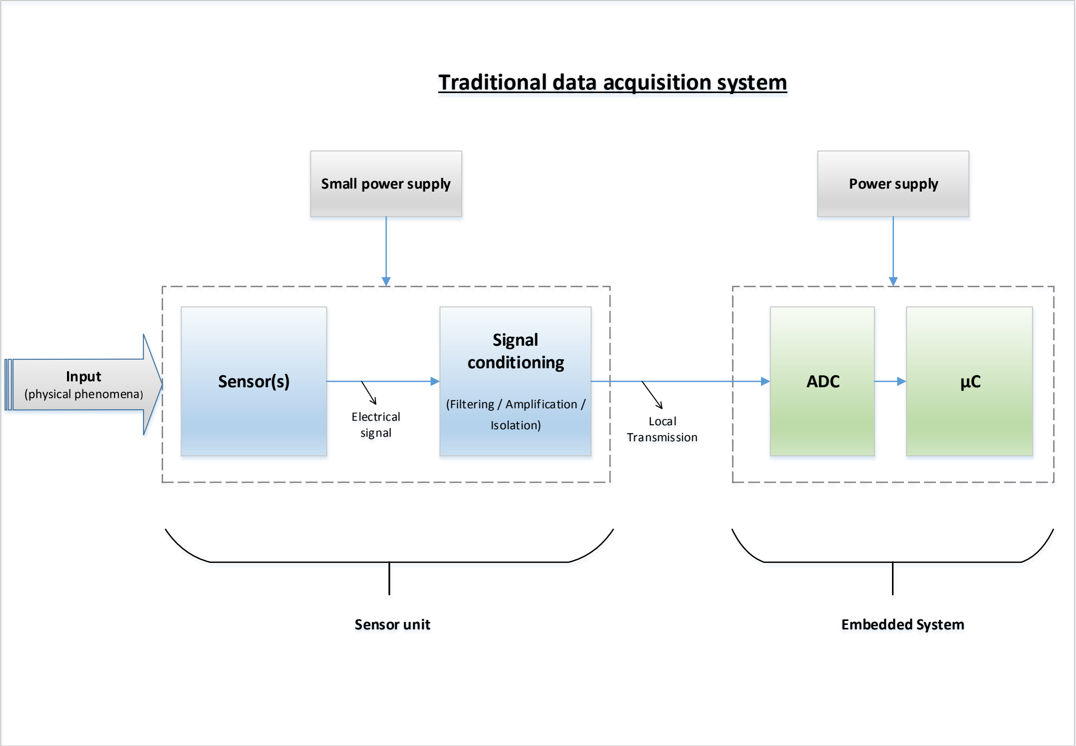


Figure 4 - Traditional data acquisition system

One or multiple sensors are converting the physical input phenomenon to an electrical signal. Possible physical quantities are amongst others vibrations, strain and temperature with outputs in the form of voltages, currents, resistance etc. (Wilson, 2004, p. 17). Typically, sensors can be divided into passive sensory systems and active sensory systems. Active sensors like strain gauges require an external power source to operate, while passive sensors like accelerometers are capable of producing their own external voltages and currents. Thus, they do not require any external power source (Wilson, 2004, p. 16). The sensor output signal can be analogue or in digital form (Storey, 2009, p. 197). Analogue signals are normally continuous signals with an infinite resolution. Digital signal are typically in binary form (0 and 1) and represent either a HIGH or LOW value, although also multi valued digital signals exist. Also, digital signals are referred to as discrete signals that can only take a finite number of values.

As already stated, the output signal from a sensor is often a small electronic signal which needs to be modified and conditioned, before further processing procedures are feasible (Wilson, 2004, p. 17). This is usually done with different types of circuits within a signal conditioning system. Typical tasks performed are signal amplification, filtering, isolation and linearization etc. The purpose of an amplification is to increase the often small output signals of sensors. Filtering is important in order to separate the signal from unwanted noise (Wilson, 2004, p. 11), which amongst others is produced by the sensor and during the amplification process (Wilson, 2004, p. 3). In many cases the sensor and the signal conditioning unit are referred to as a sensor unit while the analogue to digital converter (ADC) and microcontroller (μC) could be located somewhere else. However, there are different type of layouts, depending on the specific application. Even direct interfaces exist, where the sensor is directly connected to a digital system (Reverter, 2012). The microcontroller is simply a hidden microcomputer which translates the received signals into useful, user friendly output and is programmed accordingly (Storey, 2009, p. 698). The final output data can either be directly displayed, stored or directly communicated to other devices. Thus microcontroller consist of the same components as a microcomputer which are amongst others the microprocessor and memory. Furthermore a communications systems are essential. The microprocessor needs to communicate via its input and output sections. Furthermore, the embedded system also requires the supply of power.

For many applications it is practical to use a wireless network of sensors accompanied with various communications systems, such that a data transfer between a sensor node and the base station can be accomplished. In that case the data acquisition system differs somewhat from the traditional one. The sensor unit, signal conditioning system, ADC system, a simple microcontroller and a wireless module are needed on each node with a battery supply. The base station consist of the microcontroller, power supply and a wireless module with a power supply. Current technologies enables the integration of sensors, communications systems and digital electronics on one integrated circuit unit (IC). However, there are still challenges with wireless sensor networks. The main problem is related to remote powering. Thus, the main concern on wireless sensor networks are to minimize power consumption and package size in some cases. There are several way to do that but the most practical ones are to manage data collection rate of sensors, how frequently the data is communicated wirelessly and generally performing power management functions (Wilson, 2004, p. 576). The sensor sampling rate and transmission rate indicate how many times per second samples are taken and transmitted. During normal operation these can be kept very low and increased whenever large measurement fluctuations and incidents of interest are registered. Using the example figure from (Wilson, 2004p. 584), the current measured in a wireless strain gage system changed from 20 to 200 micro ampere as the transmission rate was increased from 1 transmission every 2 seconds to 10 transmissions per second. Theoretically this would increase battery life by a factor of 10. With a well-designed wireless sensor network operating times of 1 year and a direct range of 100 m can be achieved (Wilson, 2004, p. 587).

The simplest form of wireless communication is achieved through a star network, where one base station communicates to all sensor nodes (Wilson, 2004, p. 577). Another option is the use of a mesh network where any sensor unit can communicate with any other sensor unit. Thus, if a system is out of range other units can be used as an intermediate base for the data transfer. However, this comes at a price as power consumption is higher for a mesh network set-up.

2.7.2. Sensor technologies

In this subchapter discusses the most relevant sensor options, which are derived from Figure 2 – Design tree, sensor type).

- **Accelerometers:**

Accelerometers are sensors which are capable of measuring accelerations, vibrations and shocks (Wilson, 2004, p. 137). Although many types of accelerometers exist, the most common one is the piezoelectric accelerometer (Wilson, 2004, p. 137).

Piezoelectric accelerometers are passive sensors which are self-generating by releasing an electric signal to the stress applied on the object. A piezoelectric material is placed inside the sensor, usually connected to the sensor base at one side and a seismic mass on the other side (Wilson, 2004, p. 138). Once an acceleration is experienced by the accelerometer, a force acts on the seismic mass, which in return will put the piezoelectric crystal under stress. Piezoelectric materials act like a spring with a specific stiffness k and generate an electric signal when subjected to mechanical stress (Storey, 2009, p. 210). The IEPE (internal electronic piezoelectric) has a pre-installed signal conditioning unit. Thus, they deliver a low impedance voltage signal as output which can be easily used for further readout applications (Wilson, 2004, p. 139). Furthermore, they are popular due to a wide industrial applications range, high accuracy and low costs. It should be noticed that an external power source is needed for the IEPE signal conditioning system. Another variant of piezoelectric sensors is are charge mode accelerometers. While these sensors are more prone to environmental corruptions due to the lack of any integrated signal conditioning unit, they can operate under significant higher temperatures.

There are 3 general piezoelectric accelerometer designs. The shear mode type has piezoelectric crystals and seismic masses along the vertical centre post of the accelerometer and experiences shear forces as the base moves up and down. Thus, the charge is applied perpendicular to the force direction. This design is preferred for high frequency responses and ignore thermal transient and base bending effects to a large degree (Wilson, 2004, p. 142). The flexural mode type has a beam shaped piezoelectric element which rests on top of a fulcrum and creates signals during acceleration due to crystal bending. Since the strains are high, these sensors are more sensitive and can more easily break under large shocks. The flexure mode type is preferred for low frequencies and low gravitational accelerations (Wilson, 2004, p. 143). Finally a compression type exists. This design features a piezoelectric element which is placed between the seismic mass and the device base. Since the crystal has direct contact with the external mounting the compression mode design is generally more sensitive to base bending and less commonly used, but can withstand high loads. Although these 3 different designs feature different characteristics, individual quality can also be of importance. The main advantage of piezoelectric sensors is a combination of high durability, small package size, high accuracy and a its wide range of measurable frequencies (Wilson, 2004, p. 150). They are used for many different applications.

Another important group of accelerometers are capacitive accelerometers (Wilson, 2004, p. 146). These sensors use a circuit bridge in order to measure a capacitive change across the bridge. A seismic mass which acts as a centre electrode is placed between two fixed capacitor plates. Thus, the two fixed conductive plates are electrically separated from each other. If vibrations are present, the centre plate moves up or down, which causes a varying gap between the centre plate and the fixed capacitor plates which causes a change in capacitance. In order to make use of these measurements integrated circuits are used which for instance convert the capacitance change into practical voltage output signals. This type of accelerometer is often combined with MEMS (micro electro mechanical systems) technology (Wilson, 2004, p. 148). Capacitate accelerometers are generally very popular due to low costs. However, the frequency range and resolution are only average and they smallest packages are still considerably larger than piezoelectric sensors.

Piezoresistive accelerometers are frequently referred to as strain gauge accelerometers since they are measuring electrical resistance of materials under stress. The advantage of these sensors is its design for high frequencies. Since this design yields high stiffness the resonant frequency which causes large errors is very high (Wilson, 2004, p. 145). This characteristic makes the Piezoresistive accelerometer ideal for high shock and crash testing applications (Wilson, 2004, p. 151). While several other types and sub type of accelerometers exist, the aforementioned ones should cover the most relevant designs.

Generally accelerometers will give a greater output as frequencies increase. Looking at general vibrations there is a relation between the acceleration, frequency and amplitude of the system. A frequency denotes the number of complete cycles that a oscillating system makes per second, while the amplitude is the maximum value of the displacement (Inman, 2001, p. 8). Mathematically the relation can be written as shown below (Inman, 2001, p. 21):

$$a_{max} = A * \ (2\pi f_n)^2$$

Equation 2 - Vibrational Acceleration

Equation 2 - Vibrational Acceleration) shows how the max acceleration of a vibrating system is directly related to the product of the amplitude (A) and natural frequency (f). Thus, a larger amplitude and a larger frequency will both increase the max acceleration the system can measure. However, since the frequency is squared, its effect on acceleration is more dominant.

Typical applications of accelerometers include vibrational, shock, motion and seismic measurements. Piezoelectric accelerometers can be used for shock and vibrational measurements, while the piezoresistive accelerometers is used for shock applications due to its lower sensitivity. Capacitance accelerometers are ideal for the measurement of low frequency vibrations up to 1 kHz. Both capacitance accelerometers and piezoresistive accelerometers are often designed to operate under a 5-30 voltage (direct current) source (Wilson, 2004, p. 152). They can also operate within a wide temperature range. Depending on the specific measurement triaxial or single axis devices are chosen. In applications where movements in more than 1 direction are present a multi axial accelerometer has to be considered. Very important is the accelerometer weight as it should not exceed 10% of the test objects' weight. Mounting a heavy accelerometer on a light structure results in mass loading which negatively affects the accuracy (Meggitt Endevco, 2009).

Also the mounting procedure is a relevant parameter in selecting the right accelerometer. Typically the sensor is stud, adhesively or magnetically mounted (Wilson, 2004, p. 155). Stud or screw mounting is preferred for higher frequency measurements and offers the best transmissibility of those. However, it requires some preparation on the test objects' surface like smoothing, flattening and hole drilling. Adhesive mounting is often used when a screw is impractical to use. Using two-part epoxies offers also a high stiffness mounting. Magnetic mounting is ideal for temporary attachments of accelerometers. For best results a magnet with high pull strength and a proper attachment of the magnet to a smooth and flat surface are essential.

- **Strain Gage**

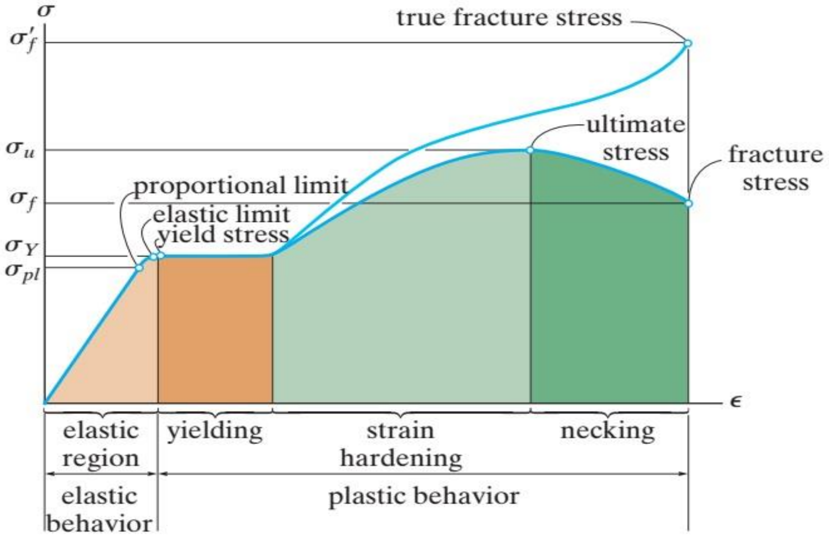
Whenever forces are applied to a body it will have influence on its shape, which is typically referred to as deformation. The extend of the deformation depends amongst other factors on material characteristics, magnitude of forces and the objects shape (Hibbeler, 2000b, p. 65). A deformation which results in a stretched body is called normal strain and defined as the objects change in length (induced by forces), compared to the objects original length before the deformation process. In equation form this can be written as:

$$\varepsilon = \frac{\Delta L' - L}{L}$$

Equation 3 - Strain

In (Equation 3 - Strain), ε is the normal strain, $\Delta L'$ is the objects total length after deformation and L refers to the objects total original length. Thus, if the object is stretched the output will be a positive strain while compression if the body results in a negative strain.

For the use of strain gages the relation between stress and strain is crucial, as these are directly related to each other depending on the used material. A figure for the stress-strain relation is shown and explained below (Hibbeler, 2000a, p. 84):



Conventional and true stress-strain diagrams
for ductile material (steel) (not to scale)

Figure 5 - Stress - strain curve (Hibbeler, 2000a, p. 84)

The elastic region follows a linear behaviour where the material will linearly elongate (stretch) as stress levels increases and return to its original shape as the stress is removed (Hibbeler, 2000b, p. 84). Mathematically the stress-strain relation can be shown with (Equation 4 – Stress vs. strain):

$$\sigma = \frac{FL}{EA}$$

Equation 4 – Stress vs. strain

In (Equation 4 – Stress vs. strain), F and L denote the force acting on the body and the bodies length respectively. E is the young's modulus, which indicates the stiffness of the material used and A refers to the objects area. After exceeding the yield stress, the plastic region is entered where the material will change permanently without returning to its original shape even as stress levels are decreased. Once the ultimate stress (maximum possible stress) is reached, stress levels will fall under further elongation of the object until the point og fracture is reached.

The most commonly used strain gages are electrical strain gages, which detect different electrical characteristics like resistance when exposed to strain (Omega, u.å.-a). The bonded resistance strain gage is the most widely used one for experimental stress analysis. Very thin wires are fixed to a carrier matrix, which in return is adhesively bonded to the specimen's surface (Figure 6 - Wheatstone bridge and strain gage principal). When the specimen like a metal object is subjected to strain it is directly transmitted to the wires of the strain gage which will strain equally as a result. The strain causes the thin wires of the strain gage to change the original length, which results in electrical resistance variation.

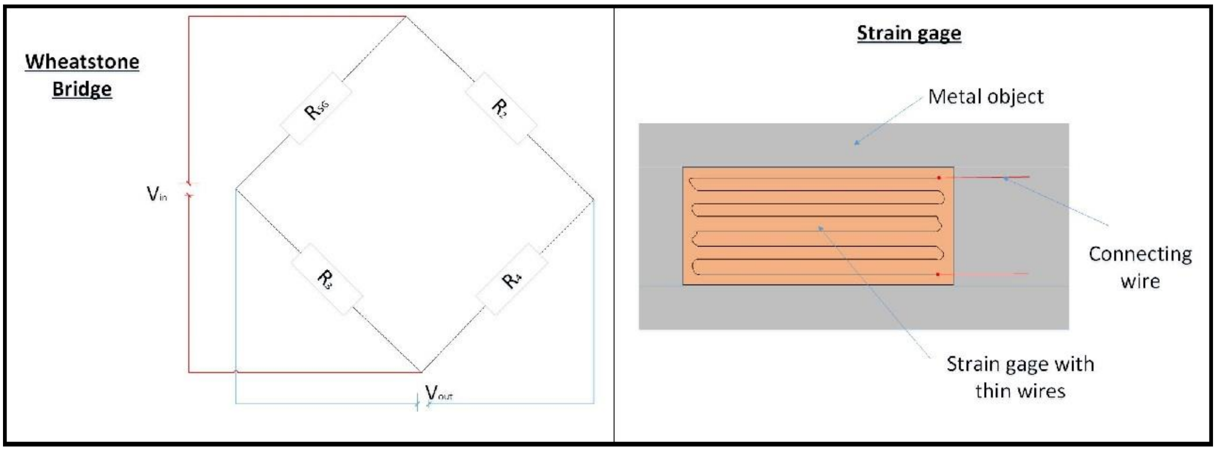


Figure 6 - Wheatstone bridge and strain gage principal

In order to measure the voltage difference due to a change in resistance, a Wheatstone bridge is often used. The 4 resistor configuration (Figure 6 - Wheatstone bridge and strain gage principal) functions as a voltage divider (Omega, u.å.-a). As long as all resistors have the exact same resistance, the output voltage will be zero. However, as soon as the strain gage (R_g), which acts as one of the resistors, changes resistance due to strain exposure the output voltage is non-zero and can be measured and translated into strain. In equation form (Omega, u.å.-a) this relation can be shown as:

$$\frac{V_{out}}{v_{in}} = (\frac{R_4}{R_4 + R_2} - \frac{R_3}{R_3 + R_G})$$

Equation 5 - Strain measurement

In (

Equation 5 - Strain measurement) the resistor values are a function of the input voltage (V_{in}), the output voltage (V_{out}). In other words, the input voltage has to be known. For that it is advised to use a voltmeter with a resistance greater than 10 GΩ and with a resolution of 1 microvolt (Omega, u.å.-a).

There are several challenges with strain gages. One is directly related to temperature. A change in temperature causes materials to strain, which can result in undesirable measurements that are not caused by external forces (Omega, u.å.-a). These temperature difference can be induced by the outside environment or through heating of the strain gage due to the input voltage. Using a high input voltage simplifies the measurement procedure due to larger outputs and higher accuracy but increases self-heating of the strain gage (Wilson, 2004, p. 507). Thus, finding the optimal excitation or input voltage is important and is typically around 3V to 10V (National Instruments, u.å.). In order to reduce environmental temperature influence, two strain gages can be used simultaneously in the Wheatstone bridge. One is actively used for measurements, while the other one is passively used as a reference for temperature corrections.

Since the output levels are rather small, noise is a major challenge. Also long wiring and unknown wire resistances can cause inaccuracies. Thus, a proper signal conditioning system has to be applied with the strain gage. If only a strain gage is purchased, a bridge completion module with the remaining reference resistors (R2, R3 and R4 in Figure 6 - Wheatstone bridge and strain gage principal) has to be manually made. Also, a signal conditioning system with amplification and noise filtering has to be included. Furthermore, the installation of strain gages has to be carefully conducted. The surface has to be smoothed and cleaned through several processes. Furthermore, the bonding with the specimen has to be tight and the correct orientation along the axis of maximum stress is crucial (Omega, u.å.-b).

- **Fracture wire:**

The principal of a fracture wire is a solely theoretical concept which might potentially function as an early warning system. The idea is to use a material which breaks before the bolt does, when subjected to deformation. An important consideration for that is given by the young's modulus (E). As mentioned in the previous section the young's modulus indicates how stiff a material is and can be identified by the slope of the stress-strain curve in the elastic region (Figure 5 - Stress - strain curve (Hibbeler, 2000a, p. 84)). Thus, rubber-like materials have low values, while steels have much higher values (Hibbeler, 2000b, p. 91). Furthermore, a material with high ductility deforms a lot before fracture, while a brittle material has very little yielding before fracture.

The eyebolts used are made of class 4.6 or 4.8 steel. Thus the fracture wire needs to be more stiff and brittle material. Assuming that the eyebolt and fracture wire would deform equally, the wire needs to fail earlier with the higher stiffness and brittleness than the eyebolt. In order to detect a breakage of the wire, an electric signal has to be sent through the wire at a certain rate. As long as the signal arrives at the other end the wire is intact and vice versa. Thus, a fracture wire could be used as an early warning system, indicating the exceedance of certain stress levels.

- **Non-contact sensors:**

Non-contact sensors are only applicable if larger position deviations are present. Thus, these sensors are not suitable to measure stresses or vibrations. The practical usage is rather related to the removal or repositioning of scaffold anchoring. Non-contact sensors could potentially register activities which include removal and location change of wall fixings.

A way to detect a change of an object position could be solved by non-contact sensors. An ultrasonic sensor for instance, functions by emitting sound waves towards a surface which then is reflected back to the sensor module (Wilson, 2004, p. 251). Since the ultrasonic pulse travels with the speed of sound, the objects' distance from the sensor can be found. Typically, the ultrasonic sound is in the range of 40 kHz, which is way above the human audible range (Carullo and Parvis, 2001). The advantage of such a system is its low price and availability.

However, there are several factors of influence on accuracy. Temperature and humidity changes change the speed of sound. Also, the reflection angle and material properties are important considerations. Foam surfaces could potentially absorb the sound (Carullo and Parvis, 2001, Wilson, 2004). It is also stated that high quality sensors can have a resolution better than 1 mm under good conditions.

A similar non-contact detection system can be established through magnetic proximity/position sensors, which can be used through the strength and direction of magnetic fields (Wilson, 2004, p. 330). These are often combined with reed switches in a system consisting of two components. A stationary reed switch is opened as long as a magnetic field is present. As the magnet moves away, the magnetic field in the reed switch reduces which eventually cause the switch to close (Harman, 1972). These systems are frequently used as cheap door and window alarms. The disadvantage is the need to use two components.

- **Wireless system**

If an interactive wireless network between sensors is made it can be used as a local positioning system, where the location of sensors can be relatively estimated compared to others. According to Patwari et al. (2005) this can be achieved with techniques like time of arrival (TOA) and received signal strength (RSS).

The signal strength technique is based on the principle that the received signal from a sensor is measured by means of its power. As the distance between sensors increases, the signal power which is measured by the receiver weakens. Thus, a change in signal strength can be related to a change in distance. The challenge with the (RSS) system is related to environmental influences on signal power. The (TOA) technique uses the speed of light as a reference velocity and translate the transmission time to the distance. Several challenges exist for TOA and the changes in time over short distances are incredibly small. However, it seems like the wireless system might be a feasible option for the application in smart scaffolds. Accuracies of up to 1 m can be achieved (Patwari et al., 2003).

3. Method

For this master thesis qualitative methods were used. Compared to quantitative data, qualitative data collection is a more explorative process which frequently allows unforeseen insights and deeper understanding of the research topic to emerge (Easterby-Smith et al., 2012). While quantitative data is primarily concerned with analytical results from a larger dataset, the qualitative data collection method rather focuses on the underlying reasons and thoughts. With this in mind, qualitative data collection seems more appropriate for answering the given research question. In order to develop a product within the boundaries of the market pull strategy, a deep understanding of the customer needs and the most significant pains and gains has to be established. Only then can a decent customer oriented design be made. Furthermore, “smart scaffoldings” would be a niche product for lager companies within the field of construction work. The number of potential respondents is thereby limited, which makes fewer but more in depth interviews more practical.

For the market research, interviews will provide the main source of data. According to Osterwalder et al. (2015), interviews are generally a quick and simple way for gaining preliminary insight into customer needs, while still being within the realistic boundaries of a 5 months master thesis in terms of resource availability. Also Yin (2013) refers to interviews as an important tool for case study evidence. However, the disadvantage for market related customer interviews is the viability of results, as customers themselves might be unsure what they really want (Osterwalder et al., 2015). Furthermore, there is a risk of data being influenced by politeness where answers reflect what the customer thinks is an appropriate response in a given situation. For practical reasons two rounds of interviews were performed, where the second round consisted on short follow-up questions via phone. Therefore these where not transcribed but notes taken and immediately drafted.

For the theoretical background textual data collection will be used. Using secondary textual data is time efficient and, if used correctly, of high quality which amongst others can provide a good baseline for general information (Easterby-Smith et al., 2012). Therefore textual data was used for the theoretical background of this thesis.

3.1. Textual data collection and general research design

In order to answer the research question in a best possible way two different main aspects have been connected and combined. The first part had the market research as a driving factor. General terms and theory around innovation strategies and smart products were combined with a market study, such that a full picture about the market potential could be derived. In order to gather these results a profound understanding of the situation and human thoughts had to be realized. This required a deep understanding about the subjects and the circumstances and has to be generalised carefully. Thus, a reasonable theoretical abstraction has been performed to translate situational findings into the application of scaffold systems and sensors. In other words, the research method for the first part is dominantly characterized by a mixture of positivism and social construction with a slight emphasis on social construction (Easterby-Smith et al., 2012, p. 53). The second part of the research included a technical feasibility study. To a large degree this part seems to be more coloured by a slightly more positivistic angle as more physical and mathematical relations with an independent observer are used (Easterby-Smith et al., 2012, p. 53). However, in the big picture the performed research is based on a mixture of positivistic and social constructionism viewpoints, since the research process is performed through theoretical abstractions and qualitative communication based data gathering. Furthermore, the study follows a rather inductive pattern. Although certain theories and expectation were established beforehand through observations (scaffolds falling over and sensors being widely applicable), clear ideas and relations were constructed through the research process of the process.

For general definitions and the theory about innovation strategies and smart product design secondary textual data has been used. The theory derived from that section was used as an input some consideration of the development and market research process. The technological feasibility also relied on secondary data, mostly technical literature and mathematical relations. The market research on the other hand used qualitative interviews as a method to collect the desired information. However, some aspects for the market research were also collected through literature in order to get more angles. Finally a very simple conceptual design example was created. The design was largely influenced by the results from all the aforementioned parts, but involved also general creativity aspects derived from logical intuitive decisions.

3.2. Interviews

In order to properly conduct interviews a decent preparation is essential. Important steps include the choice on interview structure, sampling strategy, practical set-up and interview guide preparation.

3.2.1. Interview structure

According to (Easterby-Smith et al., 2012), market research interviews should be highly structured, which implies that questions are asked in a predefined order and with a fairly narrow angle. However, since the formulated research question is angled towards a possible product idea rather than an actual physical product, it seemed more reasonable to use a semi-structured interview type. Thus, guiding questions were made prior the interview execution which changed and adopted situationally as the interview took place. While specific information of interest exists, several questions should be mad, where more open ended answers and unexpected turns are convenient. The baseline of this interview are assumption made from logical reasoning. It is expected that many scaffold accidents are happening due to missing or failed wall-mounts and that the storage of heavy components might be a partial cause of incidents (Nedrebø, 2015). It also seems logical that the use of sensor technology could be highly beneficial for scaffold operators who bear responsibility for the set-up and maintenance of scaffolds. However, the aforementioned insight does not provide the whole picture. In order to make an optimal conceptual design with sensors, it is necessary to understand the cause of problems and a sufficient understanding of contributing factors, procedures and challenges. It is important to understand the underlying problems and customer pains, with the thereby resulting opportunities, before a product solution with the right properties can be made. Customers most likely have the relevant competence in their field and can share useful information concerning the value proposition canvas. Simply put, they have a deeper understanding of the daily dealings of scaffolds. In order to obtain this information, it is critical to allow answers with a certain freedom and possible directional changes, while at the same time maintaining a basic structures where the most path finding topics are introduced. This seems to be highly equivalent with a semi-structured interview type.

3.2.2. Sampling strategy and respondent selection

Another critical step is the selection of respondents. For this particular product idea, it seems like a variety of opinions would be beneficial. Thus, the idea was to discuss the aforementioned topics with different types of companies which should have different interests and opinions about such a technology and whose experience and functions towards the scaffolding industry would be distinct. Hence, 4 main type of companies where selected:

1) Construction companies

Talking to a carpenter who uses and works daily on scaffoldings would give a good opportunity to understand the problems and gains first hand from a workers point of view, who is in regular, practical contact with scaffoldings under various conditions. Thus, their opinions and experiences might differ significant from other groups.

2) Scaffolding operators:

Frequently scaffoldings are rent and set up by scaffoldings operators. They are responsible for a proper installation and have to approve the structure before construction workers are allowed to start their work on them. Their background to scaffolds is more professional where a higher degree of technical expertise is expected.

3) Scaffolding producer / manufacturer

Since there are several scaffolding manufacturers in Norway, it would be interesting to get their opinion on this idea. They have probably the highest technical understanding and might know a lot about current technologies and recent innovations.

4) Scaffolding inspection company

These companies are third party companies which randomly inspect and verify proper use of scaffoldings. They should have a very good insight into current challenges from a large variety of inspection works.

Another important aspect to consider is the type of industry. There might be different needs and opinions between the oil and construction industry. Having interview with a selection of respondents from both industries might be very useful. Using the interest in different company types combined with different sampling strategies resulted in the final list of respondents. To a large degree a purposive sampling strategy was used. This is reflected in particular with the different company types, which are already preselected in a non-random manner. As stated in (Robinson, 2014), purposive sampling ensures that based on initial knowledge, certain pre-chosen categories are included. The type of purposive sampling strategy used in this master thesis is referred to as cell sampling. It means that important predefined groups or participants are selected before a target number of respondents is allocated to each of them. Hence, it is required that a reasonable difference between the groups exists based on solid theoretical background. For cell sampling, overlapping is allowed. (Robinson, 2014). The chosen cell samples are the 4 type of companies. Although they are all involved in the scaffold industry, they have distinctive roles, interests and tasks. Construction companies are scaffold users with the main focus on work related utility. Operators are responsible for scaffolding set-up and are mostly concerned to follow instruction procedures and safety regulation, such that the use of the finished structure matches the given circumstances. Scaffold manufacturers are manufacturing the components and are concerned to produce safe and economical viable products for the general purpose. Third party inspection companies are inspecting scaffoldings according to regulations to ensure user safety. The existing overlapping between all 4 industry branches is safety. The reasons for choosing the cell sampling strategy was to avoid that all candidates from the scaffold industry have the exact same viewpoints. Using predefined groups ensures that different and unique situations are accounted for (Robinson, 2014). The table below shortly summarises the 4 chosen sample categories and their distinguished features.

Company type	Distinguished features
Constriction companies	Practical work related usage
Operators	Set-up according to instructions and user clearance
Manufacturer	Design / manufacture of structural parts
Inspection company	Inspection of scaffolds according to regulations

Table 1 - Company type

After performing the cell sampling strategy, a target number of respondents was defined. Also, specific participants had to be selected. For that process ad-hoc and snowball sampling where used. The letter one refers to a sampling method where participants are asked for other acquaintances who might be beneficial for the process (Robinson, 2014), while the former one refers to a strategy where ease of access and availability are dominant factors (Easterby-Smith et al., 2012). A list with several plausible candidates for each of the 4 types was constructed. Since remote interviewing can be challenging due to the lack of non-verbal communication, only companies in reasonable vicinity where chosen. They were mainly contacted by phone, while in some cases further communications switched to e-mail eventually. Depending on the availability and willingness of the participants the most relevant contacts where finally selected. It was challenging to find a proper schedule that would satisfy everybody. However, it all worked out and the 6 final participants seemed to be a reasonable number considering the limited timeframe, while still providing a decent picture of the situation. A seventh participant from Beerenberg was added at a later stage, based on other's recommendations. The list with all candidates from the 7 main interviews can be found below:

Company	Type	Respondent nr.	Position
Ramirent	Operator	1	Scaffold manager
Leigland bygg	Construction	2	Carpenter
StS gruppen	Operator / *oil	3	Project manager
Sem Sikkerhet	Inspection	4	Managing director
DeltaSystem	Manufacturer	5	Managing director
Beerenberg	Operator / *oil	6	Senior engineer
WIK gruppen	Design / entrepreneur	7	Project manager / Entrepreneur

Table 2 - List of respondents

- Ramirent was originally founded in 1997 under the name Bautas and changed the name to its current one in 2010. In Norway the company had 405 employees in 2015, distributed amongst 42 customer centres. The main focus of the company is rental and service of amongst others scaffolds, construction machines and lifts (Ramirent, 2016)
- Leigland Bygg AS is a construction company founded by Mikal Leigland in 1982, but was declared a corporation in 1986. With its roughly 60 employees its field of activity involves building of houses and other architectural and building services (Leigland, 2016)
- StS gruppen offers many different HMS (health, environment, safety) services and works in particular with maintenance and modification, where scaffold jobs play an important role. Scaffolding specific tasks have been performed since 1972, with more than 10 million conducted working hours. The focus is on both offshore projects but also construction projects to a certain degree. Also scaffold sheeting is an important field for the company (StS-Gruppen, 2016).
- Sem Sikkerhet was founded in 1988 and focuses on safety for people working in heights or on the road. Scaffolding inspections by inquiry are one of the main areas the company is specialised in (Sem Sikkerhet, 2016).
- DeltaSystem is delivering various access equipment. In particular they manufacture scaffolds, halls and stair towers (DeltaSystem, 2016).
- Beerenberg is a leading service company for the oil and gas industry with a lot of focus in the fields of research and design. Some activities of the company involve ISO-services; isolation, scaffolding and surface treatment (Beerenberg, 2016).
- WIK-gruppen produces several solutions for the building and construction industry. A lot of focus is spent on entrepreneurial work, like the “liftroller”. The company works

closely together with amongst others the aluminium manufacturer Aluhak AS from Stavanger and Inventas AS from Bergen (WIKgruppen, 2016).

3.2.3. Practical set-up and execution of interviews

Finally, some practical considerations were made. The questions had to be easy to understand such that confusions could be avoided. (Easterby-Smith et al., 2012). Although some challenging question are fine, extra care has to be taken in order to define them properly. For instance, although it is advised to avoid the pitching of potential product solutions at an early stage (Osterwalder et al., 2015), a rough sketch of considered product features was made, (see interview guide) and shown to every respondent as a part of the introduction. This served two purposes. First of all it supported the process of explaining the idea in a similar manner to all participants, in order to avoid unintended manipulated outcomes due to a differently executed introduction procedures of the product idea. Secondly, it helped to give the respondents a better idea of discussed topic such that misunderstandings could be avoided. In order to reduce the chance of participant declines, the interview was designed for a duration of at most 1 hour and throughout the participant recruitment a duration of 30-40 minutes was mentioned. Intuitively that seemed to be a reasonable timeframe that managers would still invest. As longer the duration, as more participants might be scared away due to time constraints. Once the interview is performed it seems less likely that respondents have problems with a few extra minutes. In reality the average time of each interview was about 30 min. All interviews where voice recorded after an agreement from both sides and transcribed at a later stage. Throughout the interview certain probes where used. In particular mirroring which involves to repeat earlier answers in new questions and giving ideas (Easterby-Smith et al., 2012) were frequently used techniques. When transitioning from one question type to another, the main findings where usually repeated to ensure that everything was understood correctly. When more design or solution based questions were asked, example where given. For instance, on the question "what improvements on our current product idea would you suggest" was followed by an example where sensors could be used to avoid theft or undesired visitors after working hours. Also laddering up was applied in some cases, especially in the interview with Leigland bygg AS where the values and feelings of a carpenter in his daily work on scaffoldings where further investigated. Laddering up is a process where in depth question are asked to understand a person's value base (Easterby-Smith et al., 2012). A simple way of doing that is to ask "why" questions.

3.2.4. Interview guide

In order to increase the chances for a smooth execution, an interview guide was prepared, see appendix. After some warm-up and simple questions, more challenging ones followed in the main section of the interview guide. Finally the “cool down” section included some questions based on the information gathered thorough the interview. Although 9 questions were made in total, only 3 main topics of interest where examined. These are created in direct relation to the research question and should provide important data for a conceptual design, see below:

1) What are the problems and challenges in today’s scaffolding industry?

One presumption to the research question was that problems in the scaffolding industry exists. The interview topic above addresses that assumptions and investigates further if these challenges are real and what causes them if the initial guess is true. Furthermore, a conceptual design baseline might arise from the results of this topic. From an in depth mapping of current challenges, appropriate solutions can be designed and tested.

2) Which market potential has a “smart scaffolding” technology where sensors and scaffolding constructions are combined?

With this topic the intention is to get honest and elaborated feedback from respondents about his/her opinion of the presented product idea. Is there something critical missing, something we haven’t thought about? Are there better and simpler ways which essential lead to the same results? Are there any problems with our solution that we haven’t considered? These are some questions and unknowns which are hopefully answered in this part. It is also directly related to the market feasibility aspect, mentioned in the research question.

3) How can this technology be implemented and used?

The final topic discusses some more practical aspects. A potential product has to be used by a customer group, which is partially related to the market feasibility. In this section a plausible customers group could be identified such that an appealing design can be made according to its purpose and usage. In depth knowledge about the routines and preferences of potential buyers can be an important indicator for practical product features.

3.3. Data analysis of interviews and textual data

Validity and reliability are important criteria’s of any research as it increases the credibility and makes it easier for other research to arrive at similar results. In general qualitative methods do have certain limitation, since information can be differently interpreted.

According to Yin (2013), p. 240, reliability is directly related to the consistency at which a repeated research arrives at similar results. Since humans generally tend to be influenced by a certain degree of bias, which refers to expectations and experiences that reduces the researchers objectivity, information can be unconsciously interpreted different from person to person. Also, results might vary depending on the chosen respondents as their interests and views could differ. In order to minimize that problem, different customer groups have been chosen. If result are similar despite of a wide range of customer groups, it increase reliability and vice versa. In order to avoid confusions and misunderstanding about the concept of smart scaffolds the same sketch has been presented and explained to all respondents. Also validity is an important term for research. Internal validity refers to how well the selected data is measuring what it is supposed to measure (Golafshani, 2003). In other words, internal validity describes how valid the results are within the studied situation. To ensure a best possible internal validity, the interviews have been prepared carefully beforehand such that the questions were directly linked to the desired point of interest. In addition, all the interviews have been transcribed, which should improve reliability and internal validity. Reviewing the voice recording made it possible to look at the results under different circumstancing and in a repeatable manner. Although that does not prevent individual bias from influencing the results, it gives more time to actually think about responses, how they should be interpreted and how closely they answered the question of interest. Furthermore several sources of information have been connected in order to see if the results coincide and in order to get a deeper understanding of the subject. Validity is important as a conclusion is only as true as the premises it is built on. Another term of interest in research is external validity which is directly related to generalization and mostly applied to quantitative research, defined as statistical generalization (Yin, 2013. p. 40). Hence, it is not applicable to this subject. However, it is also possible to look at analytical generalization which is rather related to the applied theories. For instance mathematical and physical concepts that can be applied to new and different applications. An important restriction in that sense is the simplification of principals, which can cause fairly relevant deviations from real results. Although many simplifications have been made, they are clearly stated. For the textual analysis many theoretical connections have been made. For instance the smart products’ effect on user perception is not necessarily applicable to smart scaffolds. Therefore, these cases have also been stated and for all textual theories clear references are given.

3.4. Follow up interviews

After analysing the first round of main interviews, a second round with follow-up interviews was performed. Using the decisions from the first part of the discussion section, wall fixing seemed to be the most critical problem. In order to design a solution based on sensors, more in depth knowledge about the exact failure mode was desirable. Mostly the same participants were used for these follow up interviews and short 3-5 minute interview via the phone where performed with Ramirent, StS gruppen, Sem Sikkerhet and Delta System AS. Furthermore, Layher AS and Brenden & CO where contacted.

Company	Type	Respondent nr.	Position
Layher AS	Operator	8	Managing director
Brenden & CO	Manufacturer	9	Managing director

Table 3 - Additional respondents

- Layher AS is a daughter company of the German Wilhem Layher GmbH & CO KG. The company is specialized in scaffold manufacturing and offers a variety of scaffold based solution for the construction, ship and oil industry (Layher, 2016).
- Brenden & CO is a scaffold operator from Oslo area with about 60 employees. They rent and install a variety of scaffold systems from large industrial projects to small private projects (Brenden&CO, 2016).

These two companies were chosen in order to add another scaffold manufacturer and operator for the more technical details. Right after each of the 6 follow-up interview, a draft was written. No particular interview guide was prepared, but the relevant questions were written down beforehand. They mainly involved details about the failure mode of the wall fixings and how the forces are distributed along the walls.

4. Results

In this section the results are presented. The first part introduces the interview results and theoretical results which are closely related to market need and market possibilities. This will provide the foundation for answering the part of research question about market feasibility. The second part focuses on the technical feasibility and presents the findings of possible sensor applications. These results will then be further discussed in section 5.

4.1. Market feasibility

In order to make the development of smart scaffoldings feasible, a sufficient market potential is required. There has to be a customer need and an existing challenge or pain in the current scaffolding industry such that potential customers are willing to pay for improved solutions. The main objective with the qualitative interviews was to find out if such a marked need exists and if the development of “smart scaffolding” has a market potential. Another point of interest was to provide information about the implementation process.

4.1.1. Interviews

In total 7 interviews were performed. The interview statements in this section are therefore cited as respondent 1-7, which are related to the order given in the methodology section. With these interviews, 3 main questions have been answered.

1) What are the problems and challenges in today’s scaffolding industry?

All respondents had certain criticisms about processes and procedures in the current scaffold industry. For land based construction scaffolds the main cause of problems appears to originate from strong winds combined with user introduced negligence on tarpaulins and wall-mounts. Either of these or the combination of all 3 was the foremost mentioned cause of scaffolding accidents and critical occurrences (respondent 1, 2, 3, 4, 5, 7). In particular the wall fixings are a weak spot, as they are frequently removed and inadequately mounted during or after construction work. If too many wall-mounts are detached or incorrectly assembled during setup or use, strong winds can suddenly be a major threat. This becomes clear as different statements from several respondents (respondents 1, 2, 4 and 5, see below) are examined. The questions to these statements was about weaknesses in today’s scaffold industry.

“That scaffolds are just collapsing is almost none existing. But that wall fixings are removed or damaged during strong winds is something which happens almost after every storm”

“A relevant example is that wall fixings are being removed due to work on the facades. After finished work people forget to put them back where they belong. Or maybe they are mounted incorrectly after removal which happens quite often”

“What happens most frequently is that scaffoldings are blown down. They are falling over. And that happens often due to fixations being mounted off due to work that has to be perfumed on the wall for example. Then they are not installed after finished work or they are mounted incorrectly”

“Many workers are just taking it upon themselves and remove the wall mounts without consulting with the scaffolding operator. Actually the operator has to install them after removal”

Another cause of problems are tarpaulins. In particular on long term scaffolds it is common to use tarpaulins as a means of protecting the workers from rain and snow during working hours. The increased wind resistance requires extra care and a larger number of wall-mounts (respondent 2). In the big picture it seems that changes applied by none-professional users on wall-mounts, combined with a mixture of strong winds and tarpaulins are triggering unwanted situations. This is a complex problem as many modification on scaffold structures are performed by unauthorized workers, after the final setup and approval of professional scaffold operators (respondent 5). Furthermore, cultural differences can be challenging. A large degree of foreign workers can induce different views on safety precautions compared to Norwegian standards (respondent 2).

There are also a number of other weaknesses. For instance can overloading be the cause of failures. However, even here the problems are sometimes triggered by poorly conducted routines. respondent 5 mentioned:

“It happens that the top platform gets loaded by cranes, for instance pallets with roof tiles. They are on the topmost scaffolding plane. But the forces are going all the way done through the frame. When wall mounts are missing this can lead to overloading, because the forces that it can normally handle, are based on all the wall mounts being there according to the setup manual”

According to respondent 7, a frequent problem with overloading is also caused by misjudgement. For inexperienced workers these construction appear stronger than they actually are. In other words some workers might simply overestimate the weight carrying capabilities of scaffolds (respondent 4). However, on the other hand it seem like scaffolds in general are strong with quite conservative safety factors. This also means that several cases of theoretical overloading might remain unnoticed, simply due to the scaffold's ability to handle larger stresses than conservatively estimated. Visible deformation of some structural components are hinting in that direction (respondent 4).
Another cause of overloading might be related to scaffolds exceeding certain height limits, as the structures own deadweight already contributes to significant stresses in these cases. According to (respondent 3) standard scaffolds should not be build higher than about 50m, which unfortunately happens from time to time. respondent 5 also mentioned the importance of a proper setup, where the bottom rods are perfectly vertical. This requires the correct calibration with a bubble level. Inaccuracy during the setup of these bottom rods can result in a reduction of the structure's weight carrying capability, since the forces are not purely compressive anymore but rather create bending stresses due to decomposed force vectors.

The remaining weakness were less significant. It seems like people from scaffold operators are at some higher risk of getting hurt during the setup phase (respondent 3 and 4) partly due to poor safety-belt labelling in the instruction manuals. This can cause confusion on the correct location of safety-belts fasteners. This might lead to structural failures during a fall if the supporting component cannot handle the thereby introduced loads. Finally, improvised setups due to the lack of proper components (respondent 2) and sudden magnificent force impacts, which can result in deformed parts of structural components where mentioned as problematic in some cases (respondent 1 and 7). These impacts can occur when heavy vehicles like cranes are colliding with the structure.

2) Which market potential has a "smart scaffolding" technology where sensors and scaffolding constructions are combined?

Generally the product idea was perceived as positive and the results show that a market potential exists, under the right conditions. Only respondent 6 was very critical and expressed his doubts on the market potential of this product idea. The most likely option would be a practical related research study with these sensors according to him, but not a regular use on the construction side. His main argument was that introduced complexity, costs and time would most likely discourage potential buyers. Although the other respondents were surpassingly positive about this idea, there are still certain conditions that have to be met, before a worthwhile customer base is possible. The key words are usefulness, costs and time investment for the installation, use and maintenance. Furthermore, although such a product was perceived as a great idea, none of the respondents were actually looking or thinking about such a technology before it was mentioned. This could suggest that the need is not sufficiently high for a realistic investment willingness amongst customers. As respondent 4 and 5 stated when asked about the market potential and critical factors:

"Yes, but it has to do with the price. If it is interesting for us, it has to be interesting for the customer" ... "It is about costs all the way. They all want increased safety, but not many people pay twice the price for it"

"If the price is right, this is a great idea. Many could truly benefit from it"

respondent 1 even jokingly stated (last sentence):

"It all depends on costs and benefits. For some project it would be a useful addition. It could be an extra safety which we could offer our customers and at the same time it would give us a better assurance…Preferably it lasts forever, costs nothing and gets assembled by itself "

Clearly, the biggest challenge is to keep the price at a reasonable level, make a simple product which is easy to assemble and to find the right customer group. Respondent 5 mentioned that current wall-mount prices are as low as 50 NOK per piece. Furthermore he estimated that a doubling in price would already scare away a substantial number of customers, but might still keep 50% interested. In other words, if sensors are used on every wall-mount the retail cost would need to be as low as 50 NOK, which sounds fairly challenging.

Respondent 5 and 7 also mentioned that scaffolds are supposed to be cheap. It mostly sounded like scaffolds are perceived as a tool that people have to use in order to get the job done, but not a component where high investment willingness exists. Also there is a lot of competition which gives customers several options. Furthermore these sensors are not always required. respondent 1 for example, specifically emphasized that this technology would not be useful for all scaffolds. In certain areas like western and northern Norway where stronger winds are common, these sensors make a lot more sense than in other parts of the country. Respondent 1 also argued that scaffold on critical and densely populated areas might benefit more from improved safety. Scaffold are generally quite safe and according to all candidates little changes have been applied to the scaffolding industry the past years. All respondents mentioned that changes in material (from steal to aluminium mainly) are the only significant innovative solution the scaffolding industry has seen the past years. As respondent 3 mentioned:

"It make sense how we do it today. There are not that many alternatives. Otherwise we would already see them on the market"

On the other hand, beside a market potential for sensors on the wall fixings and sensors for the measurement of loads, there seems to be a number of different applications with market potential. Respondents 1,3,4,5 and 6 all mentioned some potential for sensors which can be used to avoid theft and respondent 3, mentioned great potential for a sensor which can count the number of workers on the scaffold and signal if the maximum number of people is reached.

Finally there appeared to be a difference in applications between oil industry scaffolding and scaffold in the building industry. Especially offshore, where hanging scaffoldings are quite common, the preferred type of sensor would measure stresses/deformation in the hinges and other critical components. This could give useful insight into current routines and how accurate and efficient current scaffolds of this form are (respondent 3, 4, 6). For the building industry, force measurements seemed less important. According to respondents 1, 2, 4 and 5 the wall-mountings and loadings would be of higher priority. Respondents 4 and 5 also mentioned new regulations which were introduced in January 2016. According to those, scaffold users are also required to get a proper introduction on the use and set-up of scaffolds. That could mean a decrease in market demand in the near future. A better technical insight might result in less incorrectly places wall fixings buy users which could solve many problems mentioned in the first part of the result section.

3) How can this technology be implemented and used?

This main topic divided the candidates mainly into two different groups. Respondents 1 and 2 argued that it would be best to sell this technology to a scaffold operators. After setting up the main structure, they could mount the required sensors, which would add extra safety. Respondents 3 and 5 on the other hand were more inclined by the idea to use these sensors as an already integrated part, which is directly purchased from scaffolding producers. While this approach might cause some trouble in case of sensors getting damaged etc., scaffold operators might not have the required competence to use and calibrate the sensors correctly (Respondent 4). Everyone argued though, that a third party company should not be included in the process as this could result in problems related to the area of accountability. In general, responsibility might be a problem. According to everyone, the responsibility today lies within the main user of the scaffold at the given time. During the set-up phase, the operator is accountable for the safety, while the responsibility shifts to the construction company as soon as they are using the structure for their work and after the scaffold has been certified by the operator. Thus, if an operator uses sensors after installation it would possibly also extend its accountability phase which might not be desirable (Respondent follow-up interview). During the follow-up interviews the majority of respondents doubted that this responsibility extension would be a major problem, but it should certainly be noticed as a potential cause of problems. Even the construction company themselves might want to invest into this technology, if it guaranties improved safety for the workers (Respondent 1, follow up interview). If an alarm goes due to critical conditions, an operator might still need a lot of time before arriving at the construction site, while some scaffold responsible workers from the construction company could fix the problem temporarily themselves before contacting the operator.

Finally, considering the theory about innovation strategies it seems reasonable, that the final development and application of this technology is moved to a different organisation. The development of the sensors should probably be made in close cooperation with a potential customer company, which could be either a scaffolding operator or a scaffolding producer. In this way, the final product can be tuned according to customer needs, which relates to the preferred market strategy, namely market pull. The table below Table 4 – Results, market feasibility) summarizes the findings:

Question type		Respondent	Score
Current problems and challenges			
Wall-fixings	Strong winds	1, 2, 3, 4, 5, 7	6
	Tarpaulins	1, 2, 3, 4, 5	5
	Changes made by users / wrong installation	1, 2, 3, 4, 5, 6	6
Overloading	Overestimation	4, 7	2
	Heavy storage	1, 7	2
	Ignored height limit	4, 6	2
Falling / set-up	Safety Belt mounting	3, 4	2
Deformations	Sudden impacts / constant overload	3, 4	2
Market potential			
Wall-mount sensors		1, 2, 3, 4, 5	5
Sensors detecting overload		3, 7	2
Sensors detecting activity and counting		1, 3, 6	3
Sensors measuring stress and strains		3, 4, 5, 6	4
Implementation			
Scaffolding operator		1, 2, 4, 7	4
Scaffolding producer		3, 5, 7	3
Construction Company		1, 7	2
Oil industry		1, 3, 4	3
Construction industry		1, 2, 4, 5, 6	5

Table 4 – Results, market feasibility

The table represents all 3 main types of question categories and how respondents replied. The first category, which focuses on current problems and challenges within the scaffolding industry includes wall fixings, overloading, falling accidents or set-up errors and structural deformations as possible problems. Furthermore, subgroups which are giving a more detailed reason for the main challenges are shown. For instance wall-fixing problems could occur due to strong winds, tarpaulins or changes made by the user/wrong wall fixing installation or a combination of them. Respondents stating a certain challenge are denoted in the right column. The second question category is centred around the market potential of wall fixings, overload measuring sensors, anti-theft/activity measuring sensors and stress/strain measuring sensors respectively. The 3rd question type concentrates on the replies about implementation and customer groups. Next to operators, manufacturers and construction companies a general grouping between oil industry usage and construction industry usage is made. The table clearly shows that wall mounts, within the construction industry are the preferred use of potential smart scaffolds, where problems are caused by a combination of strong winds, tarpaulins and incorrect use or set-up. Also stress strain measurement sensors or sensors with the capability to monitor human activity on the structure are frequently mentioned. However, especially the stress/strain measurement is in particular related to offshore platforms with hanging scaffolds. Generally the construction industry seems to be more in need of such a technology than the oil industry. The customer group selection is not that clear. There are suggestion for all 3 company types with no obvious favourite.

To conclude the results on the market feasibility, there are definitely several issues in today’s scaffold industry which can be addressed and improved. The most relevant improvements could be made on the wall fixings or related to cases of overloading. There is definitely a market potential for smart scaffolding, but a cheap, simple and time efficient product is required and it is still uncertain how certain companies perceive the technology due to the change in responsibility. Also, although the idea was perceived as potentially great, no one had put a lot of thought on the need of such a product before it was mentioned. Alternatively, new regulations could also mean that safety improvements could be made in the near future without the use of sensors. If the technology is applied it should improve safety and procedures on the wall mountings, detect overloads, measure stresses or include theft abating measures. The stress/strain measurements however, seem to be more useful for the oil sector and offshore platforms where this could provide better insight and possibly more efficiently made scaffolds in the future. A more permanent use in certain project seems to be more realistic in the construction industry, but the economic resources here are more limited. At the end it boils down to price. A reasonable priced product has to be made in order to create enough willingness to adopt the technology. The final product should then be made, using the market pull strategy in close cooperation with potential customers. Due to the disruptive nature of the technology, the product integration should be performed by a different company. That could either be a scaffold producer, a scaffold operator or the construction company. The result do not provide a clear picture on the best customer group.

4.2. Follow-up interviews

The second round of interviews were performed to gather more detailed information about the exact failure mode of the wall fixings. According to all respondents, the most commonly used variant of wall fixings are based on an eyescrew/eyebolt which is fixed to the wall. In wooden walls the eyebolt is simply installed, while a plastic hole plugs are used around the eyebolt in concrete walls. These plastic plugs will expand as the screw is installed ensuring a tight fit. Metal linkage are then used to connect the eyebolt to the scaffolding structure where it is fastened with different types of clamp systems. The two most dominant failure causes are according to respondents (1, 2, 4, 5, 8, 9):

- The first dominant failure mode happens when the whole eyescrew is pulled out. This happens in particular when the material in which the screw is installed has insufficient force carrying capacities. Respondent 5 explained that eyescrew simply installed into the cladding can be a cause of problems, as wooden cladding has limited force resistance. During installation it is crucial that places with a thicker beam behind the cladding are used. In concrete walls it is also possible that badly chosen places with damaged concrete or concrete dust can result in eyebolts getting pulled out of the holes. Besides, if eyescrew are not tightened sufficiently or loosen due to excessive vibrations they can also be pulled out eventually, especially if combined with stronger winds and tarpaulins.
- Another failure mode is caused when the whole eyescrew fractures. A insufficient bracing or fixation of the scaffold can cause extensive movement of the structure during wind. This can eventually result in fatigue or overload based fractures of the eyescrew or eyebolt.

Respondent 1 also mentioned other possible failure possibilities. He emphasized that it would be impossible to isolate a single failure mood, but that can be unique to different situations and circumstances. Also, respondent 9 mentioned that incorrectly fixed clamps can cause problems, but that newer design prevent this to a large degree. In overall, it seems like the two aforementioned situations are the most critically ones, which a sensor design should focus on. However, it might be possible that other failure mode can occur in some situations. According to all respondents incidents are caused by extensive vibrations, incorrect installation of the wall fixing, due to removal of too many wall fixings or combination of these.

According to respondent 3 and 5, the wall fixing have to be checked with tools designed to measure pull forces. Unfortunately this is not always done.

Respondents (1, 4 and 9) were also mentioning the underestimation of forces occurring due to the wind. Especially combined with tarpaulins pressure forces can get really high when the wind is blowing directly into the scaffold and towards the wall. At the same time, scaffold are usually build around a building, which means that the other side of the structure will be exposed to forces pushing the scaffold away from the wall. On that side also strong suction forces can occur. Varying wind intensities with a combination of tension and compression forces on the structure can lead to extensive movement and vibrations. However, not all the wall fixings have to take the same amount of forces. According to all respondents the highest forces are experienced on the outermost wall fixings. That is also why twice as many fixings are used at those locations, compared to the middle where the distance between wall fixings is doubled. Also respondent 2 if tarpaulins are used extra fixings have to be used for safety. What this means is that sensors are most likely not required on every wall mount. They should be primarily used along the sides of the structures and possibly at certain selected locations in the middle section.

The final results of the follow-up interviews were about the cost aspect. As only 1 specific number was mentioned during the first interview round, the follow-up interviews were used to verify these values. Respondent 1 stated that the price should definitely not exceed 50-100 NOK per wall fixing as this would double the costs and decrease interest in the technology. Respondents 4 and 9 thought 50-100 NOK per wall mount seemed a fair price. It seem like this price range is generally perceived as reasonable depending on what the technology can do and how user friendly it is.

Furthermore, the interviews as whole provided valuable information about customer requirements. Thus, a preliminary requirement table can be made be made (Figure 7 - Requirements). Since there seemed to be a general repetitive pattern in terms of requirements, these are not illustrated with the exact respondent numbers but are provided as a general understanding from the interviews.

Number	Requirement description
#1	Low cost *- 50 to 100 NOK extra per anchor*
#2	Low installation effort - *Low time consumption* - *Little calibration and adjustment*
#3	High life expectancy
#4	Robust, simple and efficient
#5	Reliable and safe

Figure 7 - Requirements

The low cost aspect has already been mentioned throughout the section. A low installation effort was also stressed frequently. The setup should be smooth, simple and fast, without the need for extensive calibrations and corrections. As higher the effort during installation, as more explicit is the use to long term scaffold structures. Furthermore, the technology must be simple and efficient. This implies that alarms are only triggered when necessary and not for all uninteresting occurrences. A high life expectancy was in particular mentioned by respondent 1. A high degree of reliability and safety is a self-explaining requirement. Since it represents the point of the technology. It should be noted that these requirement can change throughout the development process and that new requirements might be added at later stages. Besides, it is desirable to quantify the requirements as much as possible.

4.3. Technical feasibility

The technical feasibility of this master thesis consist of conceptual ideas and general consideration for the application of sensors in scaffolding. No specific solutions are provided, but useful thoughts for a potential embodied design phase are given. The conceptual designs are intended to give an input for a possible experimental set-up but do not represent the design for a final product.

4.3.1. Conceptual analysis

- **Accelerometer:**

Starting with the accelerometer, it is convenient to get a rough idea of the expected acceleration or g-forces of the system and will proved helpful information about the right accelerometer type. Using (Equation 2 - Vibrational Acceleration), a 3D plot was made in Excel to show experiences g-forces for a given range of frequencies and amplitudes (Figure 8 - Plot of free vibrational acceleration).

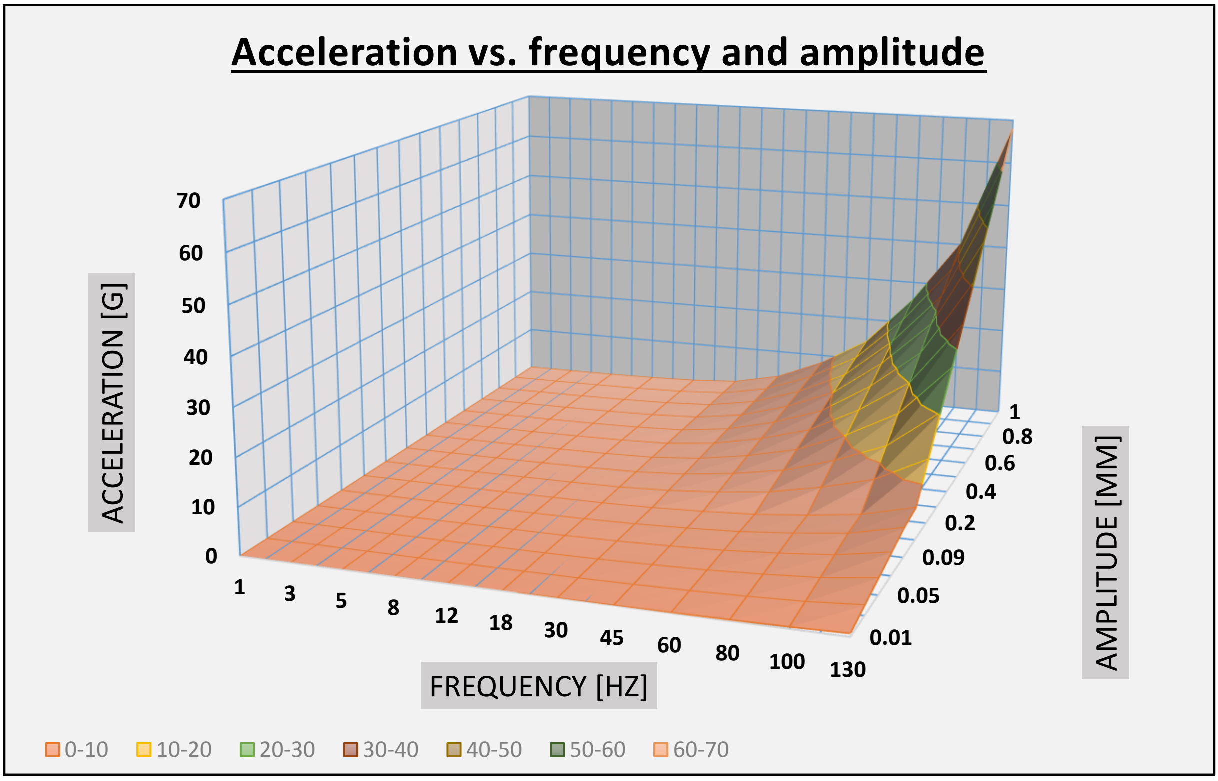


Figure 8 - Plot of free vibrational acceleration

Figure 7 clearly illustrates that higher acceleration (< 10-20 g) require at least a frequency range of about 50-130 Hz and a deflection range (amplitude) of 0.2 to 1 mm. It should be noticed that Figure 7 is solely based on a freely vibrating system. In reality it is not that simple, since the system is constantly excited by an external force. However, without a structural modelling tool it is difficult to construct an exact model.

Furthermore, using (Equation 3 - Strain), it can be found that the expected elongation of the bolt in tension is as little as 0.04 mm with a force of 1000 N, a bolt length of 8 cm, a young's modulus of 200 GPa and a bolt diameter of 12 mm. These values seem to closely resemble real values. However, the lateral deflection is most likely even smaller, since the highest forces are expected in tension. In other words, the expected amplitudes are extremely small. The wall might also have some influence on the amplitude. Since wood is more elastic than concrete the deflection of the bolt is most likely higher when applied to a wooden wall.

Using (Equation 2 - Vibrational Acceleration) with an estimated deflection of 0.04 mm from the previous paragraph and a frequency of 10 Hz results in a maximum acceleration of only 0.016 g or 0.16 m/s^2. The actual frequency is unknown and could also be much higher. For instance a frequency of 1 kHz would already result in an acceleration of 160 g. Using (Wilson, 2004, p. 151), it seems like most accelerometer types can be used for frequencies from 0.5 to 10 kHz and accelerations ranging from micro g-forces to several thousand g’s. However, these values are different for each accelerometer type. Cheap solutions might be a lot more limited and will most likely produce a lot of noise if low frequencies and small amplitudes are present. Since many factors are still unknown, a lot of experimenting and verification has to be performed.

A simple test set-up can be made using an Arduino platform with the accelerometer. This option is easy to set up and involves low costs below 800 NOK. A possible way to use an accelerometer is by the introduction of a small housing, which protects the electronic components from environmental influences and serves as a mounting platform. An example for experimental has been made in (Figure 9 - Conceptual design, parts, Figure 10 - Conceptual design, assembly and Figure 11 - Conceptual design, sectional cut assembly).

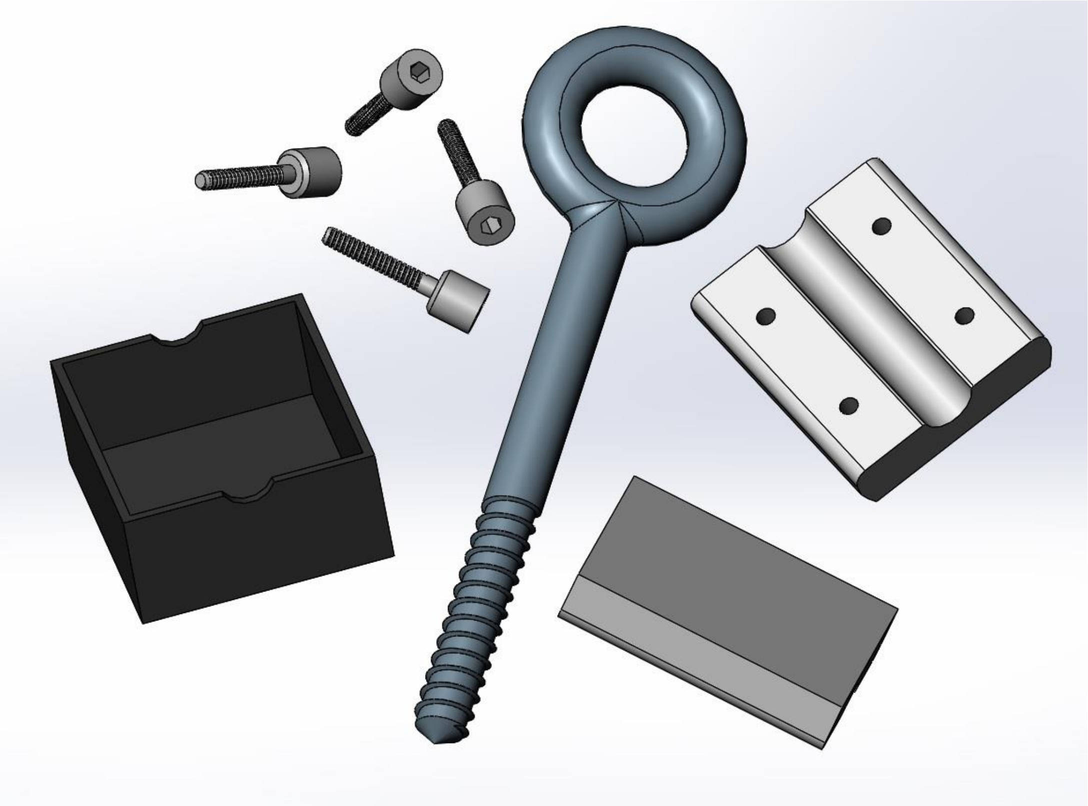


Figure 9 - Conceptual design, parts

Since vibrations are measured, the accelerometer has to be tightly connected to the eyebolt with as little as possible dampening effects. Thus a small metal clamp is introduced. On the smooth platform the sensor, circuitry and other crucial component scan be mounted and covered by a protective plastic cap.

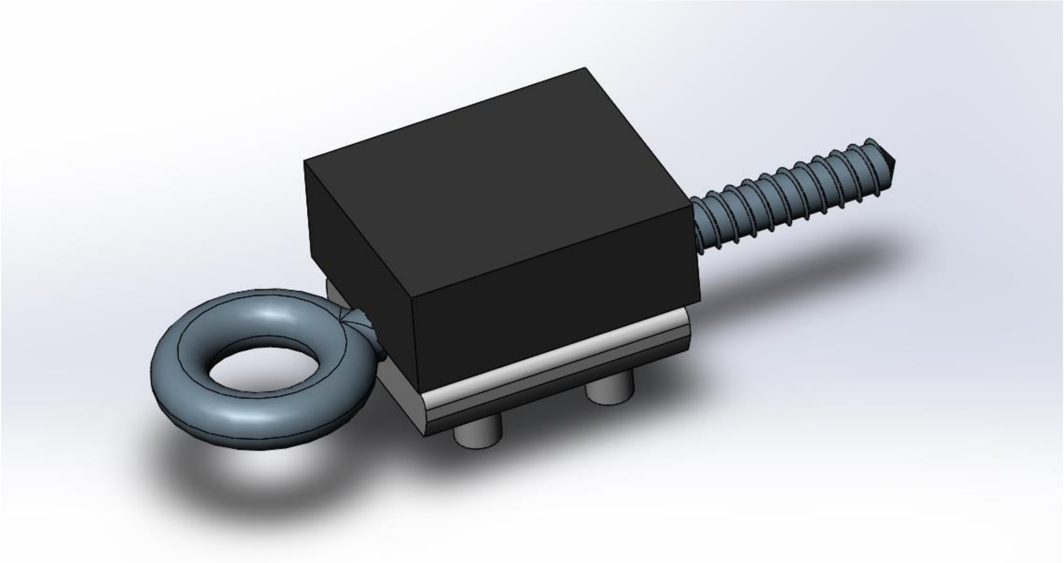


Figure 10 - Conceptual design, assembly

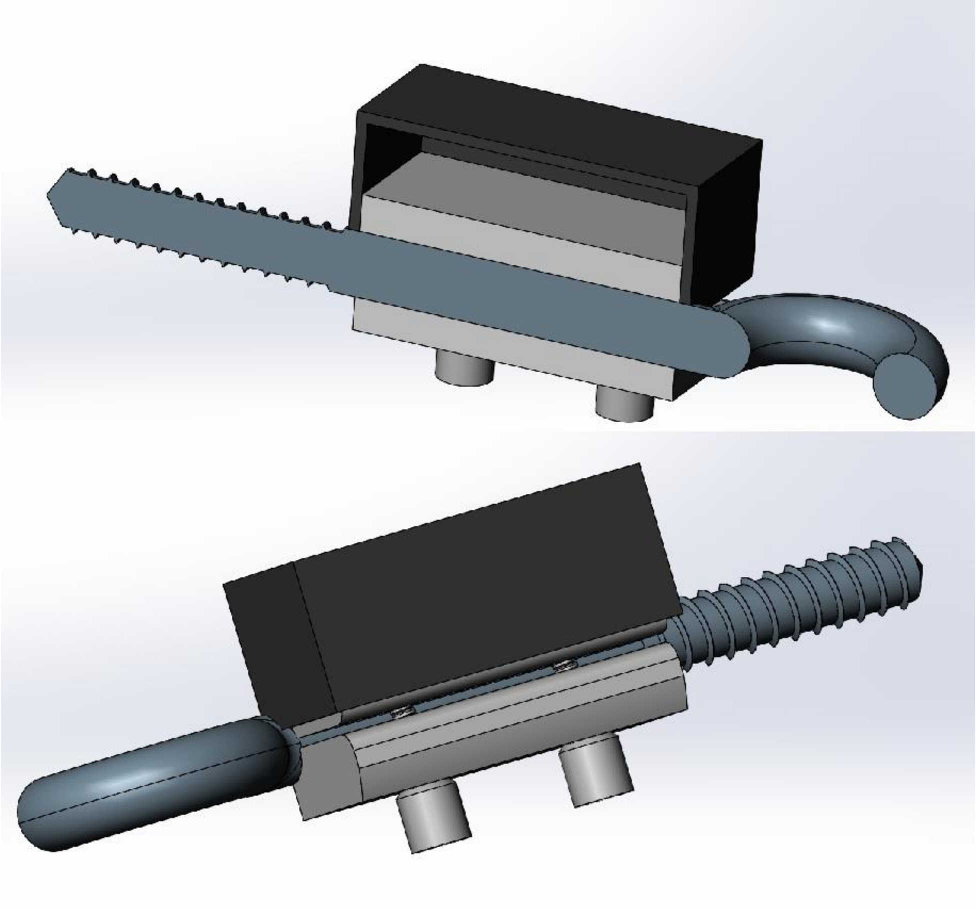


Figure 11 - Conceptual design, sectional cut assembly

- **Strain gage, fracture wire and non-contact sensors:**

The advantage of using a strain gage for the anchoring system is the direct relation between the output and stress levels. The general accuracy of strain gages is very high and should be sufficient to measure expected deformations. Using (Equation 3 - Strain) and the theoretical fact that metal gages have a measurement range of $0.1 - 40000\mu\varepsilon$ (Wilson, 2004, p. 514), deformations of 0.008µm – 3.2mm can be determined on a 8 cm long bolt. Even though these values are extreme, an elongation of 0.04mm should be within the range of what most strain gages can measure. The strain gage can be directly installed on the eyebolt if a small type is chosen. However, the disadvantage is the extensive surface preparation required before installation and initial calibrations. A proper connection between the gage and the bolt is crucial for optimal results. Since expected strain values are small, low outputs could make the setup challenging. Voltage reading are most likely in the microvolt range which requires adequate equipment. Furthermore a voltage meter is required. Using (

Equation 5 - Strain measurement) it becomes apparent that the input voltage has to be known. This can be achieved by using a large constant voltage source or by combining a battery with a voltage meter, since battery voltage tend to be somewhat unstable. Also temperature effects have to be investigated during experimental setup. For the housing a similar setup to the one in (Figure 10 - Conceptual design, assembly) can be used initially. Since the strain gage is directly mounted to the on the bolt the metal clamp system is not necessary. Nevertheless, a platform which can house and protect additional electronic components is required.

The fracture wire, while theoretically a reasonable options, seems to be hard to implement and is way beyond the scope of this master thesis. Firstly a suitable material has to be found, which is more brittle than the bolt while still being fairly conductive. Also, the wire has to be tightly fit to the eyebolt such that deformations are directly translated. A placement in the centre of the bolt might be an option. That however poses manufacturing challenges, access difficulties and overall weakening of the eyebolt. Another problem with a wire system in the centre is the neutral axis. The neutral axis is defined as an axis where no compression and tension forces apply as the specimen is bent (Hibbeler, 2000b, p. 285). Thus, a wire system in the centre would not react to bending scenarios. Although, the fracture wire system cannot measure stress directly, it can indicate when stress levels have reached a certain state. Also, temperature effects have to be accounted for and a lot of experimenting and research would be required.

Using ultrasonic and magnetic sensor is a simple option in order to detect movements of the anchoring. However, no information about stress levels or vibrations can be provided, only a repositioning of the wall anchoring can be detected. Both sensor types can easily be connected to an Arduino board and are cheap. In a possible set-up the sensor is placed close to the wall and mounted on a small platform on top of the eyebolt. For the magnetic system a small magnet has to be mounted to the wall which increases installation time. The ultrasonic sensor requires a free path through which the ultrasound is projected to the wall. Thus, the challenge is to make the system waterproof as the sensor cannot be enclosed inside a protective area. The advantage is that both systems are cheap and proven technologies. Also, the application on smart scaffold would not require high accuracies such that environmental influences are less of a concern.

- **Wireless system:**

Using a wireless system in order to register repositioning of scaffold anchors eliminates the need of non-contact sensors. A typical wireless sensor network layout is shown in (Figure 12 - Sensor distribution):

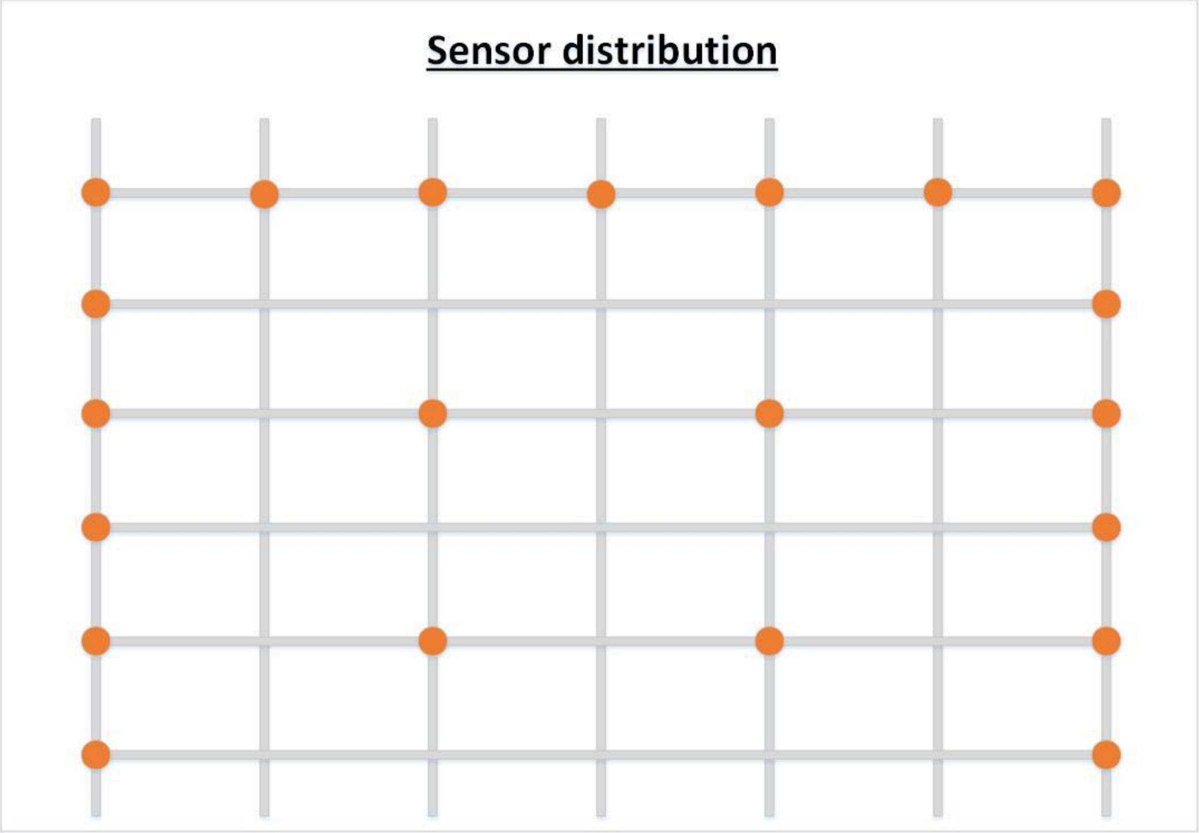


Figure 12 - Sensor distribution

Since peak loads are expected on the side and top part of the scaffolding (Wang et al., 2012), sensors are not needed on all wall fixings. As the sketch suggest, on the sides and on the top, all traditional anchoring system should be replaced by sensor based wall anchoring systems while the centre section only requires sensors on a few selected locations. Since the only required information is related to significant movements of the anchor system, the accuracy does not have to be high. A precision of 2-3 m should be sufficient for most cases. A major problem is the power consumption. Since positions based transmissions require additional power, a smart integration with proper power management is crucial. Furthermore, the local positioning system requires a mesh network where sensor communicate with the base and with other sensors. This requires more power compared to a star network.

A possible layout of one wireless sensor node is shown in (Figure 13 - Wireless sensor node)

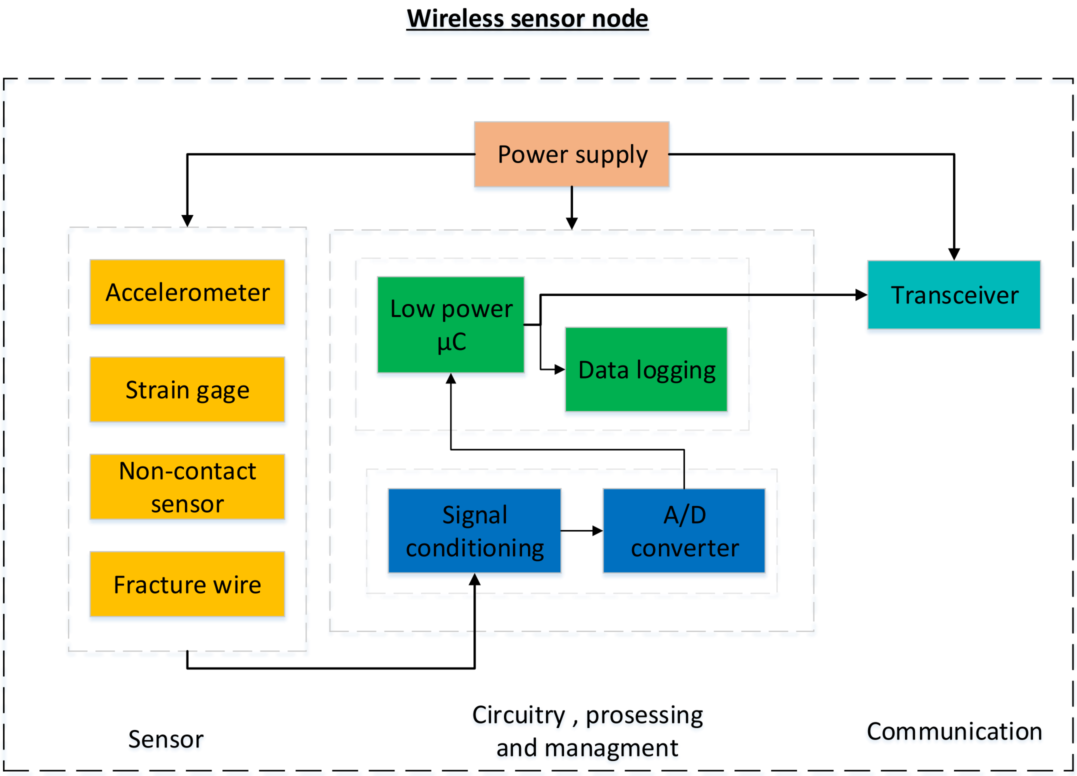


Figure 13 - Wireless sensor node

In principal, the selected sensor provides an output which is signal conditioned and converted digitally (only if output is analogue). The digital signal is then further processes and logged through the small microcontroller, which also is responsible for proper power management. Finally the data is sent to the base. Depending on the application and equipment choice, all three subsystems might require power from a battery. From this system three critical aspects become apparent; power, space and costs. Since the wall anchor is a small device, the whole wireless sensor node has to be configured within a small package. Otherwise the system becomes impractical for the user. The number of components that require power is also a concern. In particular the communication system poses power management challenges, which have to be counteracted by using smart power management solutions. Finally, the price of the equipment is important. A single sensor might not be that expansive, but all the components in the wireless sensor node could contribute to a significant costs. Although a wireless network is very practical, is does rise complexity and costs.

A summary of the most important results is shown in (Table 5 - Results, technological feasibility).

Sensor type	**Application for smart scaffolding**	
	Advantages / Possibilities	**Disadvantage / limitations**
Accelerometer	• Cheap test setup • High accuracy • Indirect stress analysis • Battery driven possibilities	• Complex data analysis model • Verification tests required • Low output expected
Strain gage	• Direct stress analysis • Very accurate measurements • Wide range of devices	• Very low output • Noise and temperature sensitive • Complex installation and calibration • Verification tests required
Fraction wire	• Theoretically a simple functioning solution • Indirect stress analysis	• Not available / research required • Hard to manufacture
Non-contact sensors	• Simple and available • Cheap	• No stress analysis • Installation time • Sealing and power consumption
Wireless system	• Automatically integrated • Sufficient accuracy	• High power consumption • Testing required • Price, space and costs

Table 5 - Results, technological feasibility

The different sensor types are listed in the leftmost column. For every sensor type the advantage and disadvantage are illustrated. It should be noticed that the accelerometer, strain gage and the none contact sensor are available in a wide range of prices, deepening on the specific type. Cheap version can be purchased for 20-200 NOK which is considered as relatively cheap. A trade off with the most preferred options is provided in the discussion section.

5. Discussion

5.1. Innovation strategy and smart product design

Due to different viewpoints in literature about appropriate innovation strategies, it is difficult to name a specific model. It appears like neither the market pull nor the technology push alone are ideal strategies considering the dynamic nature of innovations (Tidd, 2006). However, it seems reasonable to assume that smart scaffolds belong to the category of disruptive technologies since the concept is altering daily procedures and routines for the customer. An example is the sensitivity of sensor based anchors, which is significant higher compared to traditional eyebolts. If dropped on the floor, some sensor configurations might take damage. Hence, handling and storage has to be adjusted. Also, the orientation is important. Many sensors are directional sensitive and the output reliability can suffer if the deviation from the desired orientation is too high. In practical terms this implies that more care and time has to be spent on the installation procedure. After installation of all sensor systems, some calibration procedures are most likely required. Besides, if the customer wants to know the exact position of all sensors a manual sensor ID registration process might be necessary, during set-up. All these procedures come with the cost of extra set-up time.

Even if extensive experiments are performed before market introduction, a development phase with real testing under practical conditions seems unavoidable. Ideally, after successful installation the system sends notifications of some form to the user if critical measurements are registered. In reality it is likely that false alarms are triggered occasionally due do errors or unexpected situations in the starting phase.

Although smart scaffolds are disruptive, they only seem to be moderate radical products. According to Herstatt and Lettl (2004), technology push and radical innovations are closely related to a new combination of existing technologies. This would imply that smart scaffoldings are a classical situation for technology push. Also, considering the innovation-type model from Veryzer (1998) it appears like smart scaffolding are discontinuous or radical systems, since both the product capabilities of the combined product and the technological capabilities are enhanced. However, one could also argue that both sensors and scaffolds are widely accepted technologies when observed individually. Even the combination of sensors with various components is nothing radical new anymore. For instance MEMS sensors have been developed throughout the past half century, and present to near future prognoses predict a further growing market in similar technologies, particularly in the field of physical sensing (Du and Bogue, 2007). The scaffolding industry is fairly conservative in terms of innovations.

Relatively modern scaffold systems have been developed since the 70's in Norway (Alutec, u.å.) and littles has changed except of material characteristics. Thus, it seems more appropriate to consider a smart scaffold technology as moderately radical but also somewhat incremental with moderate amounts of R&D required.

Still, literature points in the direction of time consuming development characteristics for disruptive and somewhat radical innovation, in particular due to the testing and experimenting phase. Like Veryzer (1998) research suggests, an interactive relation with customers might be very important at the early development stage until specific requirements are set, followed by a more technology driven phase with development. Once the main concept is finished another customer intensive phase should be introduced such that detailed specifications are developed according to customer interest. This seems also to be more closely related to modern innovation models where customer networks and flexibility are important. Nevertheless, the nature of more radical products is a relatively high technological and market uncertainty. Hence, there seems to be a relatively high risk associated with a successful implementation of smart scaffold from an innovation point of view.

Using the aforementioned information, a possible way to proceed is the execution of some very simple and cheap technical experiments to verify the systems functioning. This can be done without heavy customer cooperation but a close connections to contact partners for sudden dynamic input suggestions should be established. Once a simplified functional product is made, more customer suggestion are collected in order to adjust detailed design parameters in accordance with customer needs. A risk is the time to market. As mentioned in (Market considerations section) long research times might weaken customer connections. Thus, a reduction in development time and a steady customer involvement might be beneficial. At the same time, a certain devotion from customer groups is an indication of hones interest. If a time and resource investment from customers groups is required the market risk might be somewhat reduced (Osterwalder et al., 2015). Call to action (CTA) is one way through which this can be achieved. Survey participation, meeting attendance and pre purchases are examples of different levels at which evidence for true customer interest can be provided.

From the literature on smart products (Rijsdijk and Hultink, 2009), certain considerations can be derived. The generalisation of this theory has to be considerate carefully though, since the aforementioned studies was not conducted on smart scaffold related products. However, some suggestion are that smart scaffoldings should operate as autonomously as possible as long as its smartness is related to cognitive related tasks. Smart scaffolds should naturally adopt cognitive tasks as the main function is related to stress based decision making on whether or not a given wall anchoring is under critical load. Furthermore, it seem like the required user involvement should be as low as possible when a reaction is activated by smart products. Thus, only critical situations should be reported. On a scaffold structure vibrations and movement are normal. If the applied sensor system is too sensitive and reports any deviation the system requires a large amount of user involvement, which is not desirable. This was also confirmed through the interviews. Also, if notifications are transmitted, it might be a good idea to reduce user involvement. It should be easy to identify the exact location at which the problem occurred and the notification should include clear information on the type of deviation. Finally, the number of functions should be kept as low as necessary. According to Rijsdijk and Hultink (2009) simplicity is preferred and a well-designed user interface is a must for multifunction products. Hence, the scaffold system should not only increase safety, but also make life easier by focusing only on relevant functionality combined with a user friendly layout.

5.2. Market feasibility

The general impression from the interviews is that plenty of challenges exist in the scaffold industry. Although local structural forces might be somewhat larger than expected, especially in combination with heavy wind loads and protective sheeting with 0% porosity (Wang et al., 2012), scaffold systems are well designed and have quite some safety margins. According to the textual data and interviews, most accidents seem to occur due to incorrect use and human errors. In addition the most likely scenario for undesirable incidents is according to most respondents either attributable to the anchoring system or due to cases of overloading. However, both are mostly triggered by human actions rather than structural or material based challenges and limitation. On one hand it implies that better solution are needed. On the other hand it seems like many problems can be solved by simply improving user knowledge and by introducing better inspection procedures. The 2016 regulation which introduces compulsory courses for all scaffold users seems to be a step in the right direction. Introducing such measures might actually reduce the need for sensors. However, if mandatory training for the use of scaffolds reduces the number of incidents is difficult to say at this state, but should become apparent in the coming years. The question is to a large degree if human errors occur due to lack of knowledge, carelessness or confusions and personal/cultural opinions.

From the results different paths can be taken. The most logical step seemed to be a further investigation into the scaffold anchoring. Since most respondents agreed on the fact that wall fixings are a weak spot it should have the largest potential. Also a solution to overloading seemed to be relevant. However, since direct force measurements were more preferred for testing and structural optimization process rather than long term daily use, it might limit the financial long term aspect. Even in the construction industry sensor based anchors would not always be useful. Densely populated areas and those frequently exposed to wind are most promising for the use of such a technology.

More specific questions revealed that the most frequent failure mode is related to the anchoring bolt getting pulled out of the wall or simply a bolt fracture. However, simplified calculations (Equation 1 - Tensile and compressive force) do not support the fracture of bolts as a likely scenario. Considering that every wall anchoring is designed to hold at least 100kg of pull force, even the smallest eyebolt with an diameter of 8 mm should easily handle forces which are up to 12 times larger in pure tension. Thus, it seems more reasonable that the screw-to-wall connection is the major problem. However, bending, shear and vibrational loads could lead to fatigue, which combined with a faulty low quality eyebolt could lead to fractures.

The biggest issue with the current market are the financial limitations. Many companies are not investing much into new technologies with the current economic situation in Norway. Furthermore, it is clear that the scaffold industry is generally limited from a financial perspective. Everything which causes a significant investment in time and money is avoided unless the direct benefits outweigh the risk. Considering this fact, it seems like in particular for the scaffolding industry any new technology needs to be very cheap and simple while still providing sufficient financial prospects. In other words, the willingness to adopt into new technologies that implicate several procedural changes, risk factors and a somewhat unknown economical aspect seems particularly low in the scaffold industry. The low number of changes within the scaffold sector in the past years could indicate the same thing. Either the need for improvements has not been apparent enough or the low financial benefits combined with high financial limitations have been factors of resistance. It seems like scaffolds are a necessity which is essential to get the job done, but not important enough to invest more than required.

Ultimately it all boils down to price, safety, effectives and simplicity. Using the data from the interviews it also became clear that safety is regarded as very important. The general reaction to a smart product which is combined with sensor technology was very positive. As the results show, all except of one respondent thought that such a product would have potential and could solve many accident related challenges. Still, no one had put any thought into it before it was mentioned. Ideally a customer has already developed a need or interest to a particular solution before it is mentioned. Furthermore, answers from interviews have to be treated carefully as customers might not be entirely aware of their real needs or prefer comfortable answers which reflect a certain degree of politeness.

As long as the product remains simple, cheap and reliable without a significant time expenditure, it seems like there certainly is a great market potential. However, if one or several of these aspects are not met, customer resistance might be high.

A possible scenario for market introduction could also be caused by regulatory support from the government. If the use of sensor technology is required by regulations the market potential would be significant and first-mover advantages would be high. However, for this to become reality, appropriate solutions through sensors must be provided, which are better than alternative options. Thus, the question is if other methods like stricter inspection and user requirements would solve the same problem in a cheaper way or not.

The results do not give any clear indications on the preferred customer group. Technically, manufacturers, operators, construction companies and third party inspection companies could be potential buyers. A manufacturer might produce eyebolts in the desired shapes and dimensions for sensor applications. An operator could certainly also have use of this technology. However, due to the induced responsibility extension, some operators might prefer to avoid a long term warning system which increases their responsibility duration. Furthermore, in case of incidents the physical distance between the operator and the construction company could be problematic. The construction company could use sensors to improve the safety of their workers. If a very cheap, simple and reliable system is introduced, construction companies might be interested. Finally, a third party inspection company could gain competitor advantages by offering a long term service with improved safety guaranty for its customers.

5.3. Technical feasibility

5.3.1. Sensor design

The first impression for the sensor design is not overly positive. There are certainly several option for a sensor based wall anchor but they all have significant flaws and several challenges need to be mastered before a functioning system is made. Getting the system to somehow work might not actually be the biggest problem, but doing so within the financial boundaries and customer requirements seems to be fairly difficult. The major challenges for the technological feasibility point of view arise from 2 contributors; sensor feasibility and wireless sensor network feasibility.

- **Sensor feasibility:**

Ideally the sensors are capable of measuring stress levels or vibrational movements. A solution which detects a critical situation due to extensive forces or incorrect installation would provide the highest benefits from a users' perspective. Out of the 3 presented suggestions for stress or movement indicator designs, the fracture wire seems to be the least desirable. Its strength would be the theoretical simplicity during operation, as only electrical pulses have to be sent through the wire to confirm an unbroken state. However, since this technology does not exist as a purchasable solution it needs to be designed and developed from scratch, thereby increasing already existing uncertainties even further. The development would be more time consuming resulting in increased time to market and higher market uncertainty. Furthermore, several technical challenges might be encounter during the development making the design impractical, more risky and technological more uncertain.

The accelerometer and strain gage designs have each their advantages and disadvantage. The strain gage seems to be a preferred choice for accurate measurements and a direct relation of the output to stress levels. In other words, the data analysis model would be simpler. The uncertainty of strain gages is to a large degree related to its hardware. Since a voltmeter with a high accuracy is needed to observe the battery driven input voltage, additional equipment has to be added which increases the overall package size and costs. The need for extensive surface preparation, calibration procedures and high temperature sensitivity reduce attractiveness even further. The use of strain gages might be a reasonable solution but a reliable system with long term accuracy in a changing environment has to be verified through testing. How accurate the strain gage will operate also largely depends on the general circuitry and other implemented subcomponents. Due to limitations in size all subcomponents on the wireless sensor node have to be in the range of only a few centimetres. In some cases this might come at a cost in terms of accuracy, noise characteristics and costs.

The accelerometer concept could potentially result in a relatively simple system with small components and a feasible package size. Furthermore, many different types of accelerometers with varying characteristics and specifications are available. The piezoelectric type is best in terms of technical performance due to its wide range of frequencies. Despite of outstanding specifications and small size variants, it seems to be too pricy for an application on scaffolding systems. Also, because of hugely varying characteristics the best suitable type for a specific application has to be determined. An alternative option is to use a much more inexpensive capacitor accelerometer which is typically powered by a 3.6 volt battery. The somewhat higher mass of more than 10-15 gram implies that a sufficiently heavy eyebolt is required such that the ratio between sensor and eyebolt mass does not exceed 10%. The frequency range of capacitance accelerometers is mostly limited to about 1 kHz (Wilson, 2004, p. 151). Since the expected frequencies on the eyebolt are still unknown, it might be advisable to conduct tests on the frequency range. A general limitation of anchor mounted accelerometers is the output data. Even if vibration values are accurately measured, the data is useless unless related effects on the eyebolt are understood. Let's assume the microcontrollers displays a significant increase in vibrational activity or indicates large vibrational spikes. It could certainly indicate that strong forces are acting on the eyescrew. However, it cannot indicate if the eyebolt is close to failure or not or what underlying reason is causing these measurements, unless data analysis models are implemented which accurately relates the events. Another problem could be caused by the relation of the frequency and amplitude (Equation 2 - Vibrational Acceleration). As long as the eyebolt is tightly fixed to the wall it should be very stiff. High stiffness should result in a larger frequency and lower amplitude. The higher frequency increases the acceleration while a lower amplitude decreases the acceleration. If the eyescrew loosens the effect on amplitude and frequency should be reversed which makes it more difficult to relate the measured acceleration with the physical phenomena on the bolt. Thus, the data analysis model is harder to implement compared to the strain gage concept. However, the accelerometer concept should provide an overall smaller and cheaper system which is less affected by environmental influences like temperature and requires less calibration. Furthermore, if a 3 axial accelerometer is chosen, measurement in x, y and z directions can be made. The strain gage on the other hand does only provide data in longitudinal direction unless several strain gages are used simultaneously.

A major concern with both the accelerometer and the strain gage is related to small output signals, due to low vibrations and deformations. Small outputs are largely affected by noise and require sensitive components in the subsystem chain. For instance, the analogue to digital converter has to provide a resolution that matches the output sensitivity of the sensor. In particular for the capacitor accelerometer, the noise levels for low amplitude vibration is a concern. Thus, experiments should to be conducted for accelerometers and strain gages in order to verify and test the practical functionality.

The non-contact sensors are a fairly safe and proven technology, but do not provide a lot of useful information when applied to wall anchors. The only purpose of these sensors is to detect removal or repositioning of the wall fixing. As shown in the result sections (Interviews), the removal or repositioning of the anchoring system by construction workers can result in accidents. Non-contact sensors can provide information in those situations, which indicates that an extra inspection should be performed by the end of the day, to ensure proper reinstallation. Although the sensor provide a cheap solution, they still need to be part of a functioning wireless sensor network which increases costs nevertheless. It seems unlikely that customers are willing to pay money for this product if a sensor-removal detection system is the only feature. It might even be possible to use the accelerometer for that task.

The wireless system could also substitute the non-contact sensors. Since a wireless system is required anyway, it seems reasonable to extend its functionality to also register sensor node displacement or removal. Accuracy requirement are not that high but a proper functionality has to be verified through testing procedures. In addition a proper power management is crucial, to avoid excessive power consumption due to a wireless positioning system. In particular the received signal strength technique might be interesting as long as regular calibration procedures are performed such that environmental effects can be accounted for.

It also seems most appropriate to simplify the functionality as much as possible. Thus, emphasis should be put on either the measurement of stresses and vibrations or solely on the removal and repositioning of wall anchoring. Achieving a functionality og both parameters through different sensors increases complexity and costs. Thus, the focus on either the accelerometer or strain gage concept seems appropriate. Only offering an anchor removal warning system will most likely not provide sufficient benefits for the customer to outweigh the costs. Alternatively extra functionality with a non-contact sensor could be added at a later stage.

- **Wireless sensor network feasibility:**

A wireless network seems to be most the realistic solution for a smart scaffold system. Although a lot of advancements have been made in this area, challenges remain. In particular for wall anchoring, a major concern is the package size since everything should fit within the housing. As illustrated in Figure 13 - Wireless sensor node), a sensor node consists of many subsystems. Care has to be taken that small components are selected without compromising the sensor feasibility. Another drawback is the price, since small and accurate solutions might be more expensive. This needs to be further investigated. Finally, the power budget needs attention. Since the wireless communication requires a lot of power, the battery lifetime can be a problem. The first way to solve this is to minimize transmission rates. It seems reasonable to assume that measurements are not needed continuously. A proper power management could be programmed which only collects data every 30 min, which then is sent to the base. Between these measurement intervals, the system is put in a sleep mode which reduces power consumption drastically. Even if the wireless network is used for anchoring position purposes there is no need to constantly register the local position of all sensor nodes. The exact transmission and sampling rates have to be tested and adjusted according to optimum performance. Another way to reduce the power issue is to install rechargeable batteries. In that case, the battery lifetime only has to last for the operational timeframe of the scaffold. Once the scaffold structure is relocated or removed the sensor notes could be charged. This could reduce battery lifetime expectations from 1 year or more, to only a few months. However, for very large projects where the scaffold is used over a very long periods, rechargeable batteries might not be that beneficial.

For further testing it seems logical to prioritized sensor feasibility. Once a proper functionality is verified and suitable products found, the wireless sensor system can be tested and designed accordingly.

In general it seems like the complexity of a wireless sensor network for the wall anchoring is fairly complex. Although costs are low for single components, the whole set-up with the sensor, circuitry, microcontroller, power package and communication module can be significant higher. From the performed interviews the impression is that cost related margins are low, with an according price range of 50-100 NOK per wall anchoring. It seems unlikely that the entire sensor node will fit this budget. Thus, the technological risk appears high. However, the investment for a simple experimental set-up is low. Many critical parameters could be tested, verified or falsified for less than 1000 NOK. Thus, it might be reasonable to conduct some simple tests before jumping to a final conclusion.

5.3.2. Sensor implementation

The last part of the discussion briefly addresses some practical considerations which are directly related to Figure 3 - Practical considerations)

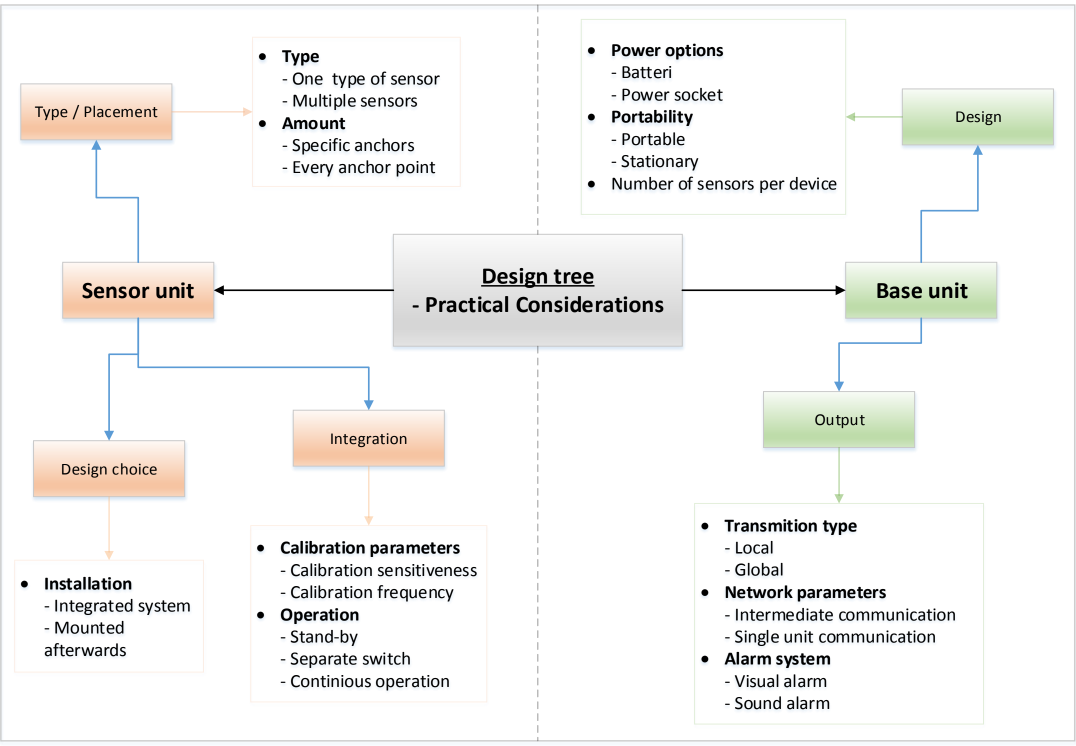


Figure 3 - Practical considerations), based on knowledge and experience gained throughout the research process. It seems like one specific sensor design should be selected, instead of using multiple sensors. First of all the technological uncertainty is already high and should not be increased further by multiple designs. Secondly, the customer might react negatively on increased complexity. The sensors should only be placed on critical locations, instead of all anchoring positions. It is unlikely that wall fixings in the middle will prior the side and top mounted ones., since forces should be highest on the side and top locations. Even if centred anchors would fail or a critical number would be removed, the effects should be measurable, as stress concentrations on the remaining anchors increase. However, the cost reductions by only using selected locations could be significant, allowing for higher sensor node prices. The sensors and circuitry should be integrated in order to guaranty functioning and proper environmental protections. In this way, calibrations and critical preparations can be made beforehand and the user only needs to focus on an appropriate installation of the anchoring system. Since the wireless sensor nodes are battery driven a sleep function during inactivity should be included.

The base unit needs to have a very appealing user interface. Portability would be beneficial, as a construction area is subjected to frequent changes and adjustment. Weather the base unit is battery driven or power through a regular power supply has to be determined as the product is developed. A battery would most likely be the preferred choice, as long as battery lifetime is reasonable. The number of units per base should be as high as possible. If several bas units are needed for the same construction area, user-friendliness would suffer and prices would increase. If distances are larger than the general capability of the wireless communications allows, intermediate sensors can be used to transfer the signal. The most critical part is related to individual sensor locations. While a received signal strength technique can detect movements, it might be difficult to use it for exact position determination. Every sensor node can be equipped with its own ID tag, which makes it possible to identify each individual sensor. However, it might still be necessary to manually register the location of each sensor compared to the neighbouring nodes or to implement a model which visually illustrates the location of every noted compared to the other sensors.

It seems likely that the setup of a smart scaffold would increase the wall anchoring installation time. The requirement for further adjustments and initial calibration suggests that this technology is only preferred on long term projects, where the scaffold structure is used for an extended period of time. Since loads and forces increase with structure size the application of sensors is devoted to larger industrial scaffold systems.

As a closure for the discussion section a short trade-off table is provided which is based on estimations and the overall impressions obtained throughout the data collection process.

Criteria's		**Accelerometer**	**Strain-gage**	**Fracture Wire**	**Non-contact sensor**	**Wireless sensor network**
Market feasibility	**Low**			x	x	
	Medium	x	x			x
	High					
Technical feasibility	**Very Low**			x		
	Low	x	x			x
	Medium					
	High				x	
Requirement fulfilment	**Low**				x	
	Medium					
	High	x	x	x		x

Figure 14 - Trade-off table

The accelerometer, strain gage and wireless network receive a medium score on market feasibility. Considering that the requirement fulfilment of these systems is high but also more expensive then 50-100 NOK this score seems reasonable. It should be noted that the high requirement fulfilment is only valid if full functionality is verified and all technical problems solved. The fracture wire would also have a high requirement fulfilment (if it works as intended), but do to a higher time to market, more development and most likely higher development costs the market feasibility still appears low. The non-contact sensor are a cheap solution, but integrated in a system with wireless capabilities, the system price might only be marginally lower compared to other solutions. Since the functionality of a non-contact sensor is limited, it can only fulfill the most fundamental requirements (removal and repositioning). Thus, customers would probably be fairly sceptical investing into such a system, which makes the market feasibility for non-contact sensor low, despite of a high market feasibility.
As a result, the strain gage or accelerometer combined with a wireless network seems to be the most likely solution. The risks are still high and a low technical feasibility combined with a modest market feasibility does not seem to provide great prospects. However, if the technical challenges are solved and a low cost option found, a further development process might be more interesting.

6. Conclusion

This master thesis was initiated with by the following research questions:

“ Is technological brokering of smart products in the fields of sensor technology and scaffolding feasible, when looking at technical and market based parameters? ”

The initial assumption of existing challenges and safety flaws on scaffolding has been confirmed by literature and interviews. The results clearly indicated that most incidents are attributable to human errors and user inconsistencies. In particular the wall anchoring has been identified as a major cause of scaffold related accidents. More specifically, the eyebolt which connects the scaffold system to the wall, appears to be a common trigger point for failures and formed the foundation for the technological feasibility analysis. A combination of incorrect installation and insufficient anchor points, as a result of faulty setup or subsequent user-introduced configurational changes, causes the eyebolt to either be pulled out of the wall or to simply fracture.

The technological results indicated the presence of major challenges, which need to be overcome before a wireless sensor network for increased scaffold safety is viable. Even the most reasonable concept, which is based on either accelerometers or strain gages, requires an extensive practical testing phase before a proper functionality can be truly verified or falsified. However, a highly simplified analysis suggested that only minor deformations and vibrations are expected on the eyebolt. Consequently, small sensor output values are anticipated which requires components with sufficient sensitivity, accuracy and proper noise reduction techniques. Another major concern is related to the wireless system. While technological solutions certainly exist, limited space and power availability per sensor node, combined with significant budget restriction make a practical implementation challenging. As a result, the technological uncertainty is presumed to be high.

Considering the market potential, the interview data clearly indicates a positive perception of the proposed product solution amongst potential customers. On the downside, no one had put a lot of thought on the need of such a technology before it was mentioned. The overall impression of the scaffold industry is a mixture of high economical limitations and relatively modest innovation willingness. Furthermore, new user based regulations which were introduced in January 2016 might improve scaffold safety in an alternative way. Ultimately, it boils down to price, safety, effectiveness and simplicity. As long as the proposed product remains simple, cheap and reliable, without a significant time expenditure, a market potential certainly exists. However, it seems like these requirements are sensitive to change. Consequently the market uncertainty is relatively high.

From the theoretical background it seems like the overall innovation potential of technological brokering and smart product design is high and offers several advantages. Nevertheless, the application of the aforementioned innovation method on scaffold systems is less desirable. Considering the strict practical, technical and economical requirements, the market feasibility seems moderate while the technological feasibility seems rather low. The high market and technological uncertainty, combined with a significant risk associated with discontinuous technologies, might outweigh the potential benefits. However, this decision is based on individual perspectives and might also change with technological progresses in the future. Since initial experiments could be conducted without a significant investment and risk, it seems reasonable to perform practical tests if further development is desirable.

6.1. Implications, limitations and future research

Throughout this research a lot of interesting aspects have been revealed. However, particularly the technological feasibility could only be conducted in a simplified manner, which opens a lot possibilities for further research. In particular, the functioning verification of accelerometers and strain gages for a smart scaffold application requires a lot more attention. Ideally, more complex models are applied and simplified experiments conducted. More research is also required in wireless sensor networking. Although several technological solutions exist, the power requirements and package size for certain applications are still a challenge. Considering the vast potential of these this technology a lot innovations possibility could arise from wireless sensor systems.

There are also several limitations to be addressed. In technical terms a lot of changes and improved technologies, make is challenging to provide an up-to-date overview. Some of the sources are a few years old and a lot might have changes already. Also the interview method is not bullet proof. Although care has been taken, several uncertainties remain when conducting qualitative and quantitative studies.

7. References

ABERNATHY, W. J. & UTTERBACK, J. M. 1978. Patterns of industrial innovation. *Technology review,* 64**,** 254-228.

ALBY BYGGMESTER. u.å. *Aluminium Stillas monteringsveiledning* [Online]. Available: file:///C:/Users/Chris/Downloads/Monteringsveiledning_ALBY_Stillas.pdf [Accessed 03.05 2016].

ALUTEC. u.å. *Alutec om oss* [Online]. Available: http://www.alutec.no/Om-oss/Historikk [Accessed 06.04 2016].

ARTS, S. & VEUGELERS, R. 2014. Technology Brokering and Breakthrough Invention.

ASHEIM, B. & GERTLER, M. S. 2005. The geography of innovation: regional innovation systems. *The Oxford handbook of innovation***,** 291-317.

BEERENBERG. 2016. *Om selskapet, Beerenberg* [Online]. Available: http://www.beerenberg.com/Om-Beerenberg/Om-selskapet [Accessed 27.04 2016].

BREM, A. & VOIGT, K.-I. 2009. Integration of market pull and technology push in the corporate front end and innovation management—Insights from the German software industry. *Technovation,* 29**,** 351-367.

BRENDEN&CO. 2016. *Om Brenden & CO* [Online]. Available: http://www.brenden.no/om-brenden-a-co.html [Accessed 27.04 2016].

BUURMAN, R. D. 1997. User-centred design of smart products. *Ergonomics,* 40**,** 1159-1169.

BYGGSYSTEMER. u.å. *Stillas* [Online]. Available: http://www.byggesystemer.no/stillas.353241.no.html [Accessed 02.05 2016].

CARULLO, A. & PARVIS, M. 2001. An ultrasonic sensor for distance measurement in automotive applications. *IEEE Sensors journal,* 1**,** 143-147.

CO-OPERATION, O. F. E. & DEVELOPMENT 1997. *The measurement of scientific and technological activities: proposed guidelines for collecting and interpreting technological innovation data: Oslo manual*, OECD.

COOPER, R. G. 1983. A process model for industrial new product development. *Engineering Management, IEEE Transactions on***,** 2-11.

DELTASYSTEM. 2012. *Assembly, instruction ALEX* [Online]. Available: http://www.deltasystem.co.uk/upload/Monteringsanvisning-ALEX-R2012-01-engelsk.pdf [Accessed 02.05 2016].

DELTASYSTEM. 2016. *Om Delta system AS* [Online]. Available: http://deltasystem.no/om-oss/ [Accessed 27.04 2016].

DELTASYSTEM. u.å. *Stillas* [Online]. Available: http://deltasystem.no/stillas/ [Accessed 05.02 2016].

DU, H. & BOGUE, R. 2007. MEMS sensors: past, present and future. *Sensor Review,* 27**,** 7-13.

EASTERBY-SMITH, M., THORPE, R. & JACKSON, P. R. 2012. *Management research*, Sage.

FISCHERNORGE. u.å. *Stillasinfestning* [Online]. Available: http://www.fischernorge.no/PortalData/9/Resources//STILLASEINNFESTING_KAP.pdf [Accessed 03.05 2016].

GOLAFSHANI, N. 2003. Understanding reliability and validity in qualitative research. *The qualitative report,* 8**,** 597-606.

HARGADON, A. & SUTTON, R. I. 1997. *Technology brokering and innovation in a product development firm*.

HARMAN, B. 1972. *Magnetic door alarm*.

HERSTATT, C. & LETTL, C. 2004. Management of" technology push" development projects. *International Journal of Technology Management,* 27**,** 155-175.

HIBBELER, R. 2000a. Conventional and true stress-strain diagrams for ductile material, Fig. 3-4. Prentice Hall, Upper Saddle River.

HIBBELER, R. 2000b. *Mechanics of Materials (2000)*, Prentice Hall, Upper Saddle River.

HIBBELER, R. C. 2013. *Statics and mechanics of materials*, Pearson Higher Ed.

HOWELLS, J. 2006. Intermediation and the role of intermediaries in innovation. *Research policy,* 35**,** 715-728.

INMAN, D. J. 2001. *Engineering vibration*.

INVENTAS. u.å. *Inventas AS, Om Inventas section* [Online]. Available: http://inventas.no/om-inventas/ [Accessed 06.04 2016].

JONES, G. R. & EDUCATION, P. 2010. *Organizational theory, design, and change*, Pearson Upper Saddle River.

KLAUS BØRRINGBO & BRAATHEN, F. 2016. *Så hardt vil endringene ramme jobben din* [Online]. Available: http://www.aftenposten.no/okonomi/Sa-hardt-vil-endringene-ramme-jobben-din-8332560.html [Accessed 20.05 2016].

LAYHER. 2016. *Layher Stillassystemer* [Online]. Available: http://www.layher.no/ [Accessed 27.04 2016].

LEIGLAND. 2016. *Historikk, Leigland bygg AS* [Online]. Available: http://www.leiglandbygg.no/no/sider/Historikk/ [Accessed 27.04 2016].

LOVDATA KAP. 17 ARBEID I HØYDEN 2016. § 17-2. Krav til opplæring ved montering, demontering, endring og kontroll av stillas med øverste stillasgulv fra to meter.

MALTHUS. 2016. *Stillas Presenning* [Online]. Available: http://www.malthus.no/byggutstyr/v%C3%A6rbeskyttelse/stillas-presenning [Accessed 29.04 2016].

MCDERMOTT, C. M. & O'CONNOR, G. C. 2002. Managing radical innovation: an overview of emergent strategy issues. *Journal of product innovation management,* 19**,** 424-438.

MEGGITT ENDEVCO. 2009. *Practical understanding of key accelerometer specifications* [Online]. Available: https://www.endevco.com/news/archivednews/2009/2009_09/TP328.pdf [Accessed 09.05.2016 2016].

MÜHLHÄUSER, M. 2007. Smart products: An introduction. *Constructing ambient intelligence.* Springer.

MYRSET, O., HIRTH, M. & STANGELAND, G. 2016. *Statoil deler ut kontrakter for 11 milliarder kroner* [Online]. Sysla. Available: http://sysla.no/2016/01/05/oljeenergi/statoil-tilder-kontrakter-verdt-11-milliarder_72571/ [Accessed 11.05 2016].

MYSEN, A. G. u.å. Smart Products, An introduction for design students. 11.

NATIONAL INSTRUMENTS. u.å. *Strain Gauge Measurement – A Tutorial* [Online]. Available: http://elektron.pol.lublin.pl/elekp/ap_notes/NI_AN078_Strain_Gauge_Meas.pdf [Accessed 17.05 2016].

NEDREBØ, R. 2015. *Manglende veggfeste kan forklare stillaskollaps* [Online]. Stavanger Aftenblad. Available: http://www.aftenbladet.no/nyheter/lokalt/stavanger/Manglende-veggfeste-kan-forklare-stillaskollaps-3668352.html [Accessed 25.04.2016 2016].

OMEGA. u.å.-a. *Practical strain gage measurment* [Online]. Available: http://www.omega.com/techref/pdf/StrainGage_Measurement.pdf [Accessed 10.05 2016].

OMEGA. u.å.-b. *Strain gage installation* [Online]. Available: http://www.omega.com/Pressure/pdf/REF_straingage_install.pdf [Accessed 17.05 2016].

OSTERWALDER, A., PIGNEUR, Y., BERNARDA, G. & SMITH, A. 2015. *Value Proposition Design: How to Create Products and Services Customers Want*, John Wiley & Sons.

OTTOSSON, S. 2004. Dealing with innovation push and market need. *Technovation,* 24**,** 279-285.

OVERSIKT OVER ENDRINGER FRA 1.1.2016 - ARBEID I HØYDEN 2016. Forankring av stillaser § 17-18.

PAHL, G. & BEITZ, W. 2013. *Engineering design: a systematic approach*, Springer Science & Business Media.

PATWARI, N., ASH, J. N., KYPEROUNTAS, S., HERO III, A. O., MOSES, R. L. & CORREAL, N. S. 2005. Locating the nodes: cooperative localization in wireless sensor networks. *Signal Processing Magazine, IEEE,* 22**,** 54-69.

PATWARI, N., HERO III, A. O., PERKINS, M., CORREAL, N. S. & O'DEA, R. J. 2003. Relative location estimation in wireless sensor networks. *Signal Processing, IEEE Transactions on,* 51**,** 2137-2148.

PROFFSTILLAS. u.å. *Tungstillas* [Online]. Available: http://proffstillas.no/tungstillas/ [Accessed 02.05 2016].

QUICKALLY. u.å. *Aluminium vs. Steel* [Online]. Available: https://quickally.com.au/resources/aluminium-vs-steel [Accessed 02.05 2016].

RAMIRENT. 2016. *Om oss, Ramirent* [Online]. Available: http://www.ramirent.no/om-ramirent.aspx [Accessed 27.04 2016].

RAO, S., AHMAD, A., HORSMAN, W. & KAPTEIN-RUSSELL, P. 2001. The importance of innovation for productivity. *International Productivity Monitor,* 2**,** 10.

REVERTER, F. 2012. The art of directly interfacing sensors to microcontrollers. *Journal of Low Power Electronics and Applications,* 2**,** 265-281.

RIJSDIJK, S. A. & HULTINK, E. J. 2009. How Today's Consumers Perceive Tomorrow's Smart Products*. *Journal of Product Innovation Management,* 26**,** 24-42.

ROBINSON, O. C. 2014. Sampling in interview-based qualitative research: A theoretical and practical guide. *Qualitative Research in Psychology,* 11**,** 25-41.

ROGERS, M. 1998. *The definition and measurement of innovation*, Melbourne Institute of Applied Economic and Social Research Parkville, VIC.

ROTHWELL, R. 1994. Towards the fifth-generation innovation process. *International marketing review,* 11**,** 7-31.

SAFWAY SERVICE. 2010. *Safety issues wind* [Online]. Available: http://www.safway.com/search_results.asp?cx=006721147141313471021%3Aga9gteg-qpc&cof=FORID%3A11%3BNB%3A1&q=wind+issue&as_filetype=&sa.x=0&sa.y=0&sa=Search [Accessed 29.04 2016].

SARASVATHY, S. D. & VENKATARAMAN, S. 2011. Entrepreneurship as method: open questions for an entrepreneurial future. *Entrepreneurship Theory and Practice,* 35**,** 113-135.

SEM SIKKERHET. 2016. *Om oss, Sem Sikkerhet* [Online]. Available: http://www.semsikkerhet.no/Om-oss [Accessed 27.04 2016].

SOLIDEQ. 2014. *ALUSCAF spirstillas Monteringsanvisning* [Online]. Available: http://www.solideq.no/uploads/documents/ALUSCAF%20monteringsanvisning%20R01-2014.pdf [Accessed 02.05 2014].

SOLIDEQ. u.å. *Aluscaf spirstillas i aluminium* [Online]. Available: http://www.solideq.no/no/stillas/spirstillas/aluscaf-spirstillas [Accessed 02.05 2016].

STABENFELT, S. A. B. R. S. L. I. D. I. T. H. I. B. D. H. 2015. Rapport etter tilsyn med stillasbransjens håndtering av opplæring, avviksbehandling og oppfølging av hendelser. Petroliumstilsynet.

STANGELAND, G. 2016. *Se bildene av stillasslurvet på norsk sokkel* [Online]. Sysla. Available: http://sysla.no/2016/01/20/oljeenergi/se-bildene-av-stillasslurvet-pa-norsk-sokkel_74371/?utm_source=bt&utm_medium=webwidget&utm_campaign=promo [Accessed 11.05 2016].

STILLASENTREPRENØRENES FORENING. 2013. *Definisjon og oppmåling av stillas* [Online]. Available: http://www.nsg.as/wp-content/uploads/2015/12/definisjoner-for-stillas-bygg-og-anlegg.pdf [Accessed 02.05 2016].

STOREY, N. 2009. *Electronics: a systems approach*, Pearson Education.

STS-GRUPPEN. 2016. *Stillas, StS gruppen* [Online]. Available: http://www.stsgruppen.com/nb/tjenester/stillas [Accessed 27.04 2016].

TIDD, J. 2006. A review of innovation models. *Imperial College London,* 16.

TÖDTLING, F., LEHNER, P. & KAUFMANN, A. 2009. Do different types of innovation rely on specific kinds of knowledge interactions? *Technovation,* 29**,** 59-71.

US-BLM 1990. *H-9102 Metric handbook*.

VALAKER, E. L. H. O. 2013. *Stillas veltet i Sandviken* [Online]. Bergens Tidende. Available: http://www.bt.no/nyheter/lokalt/Stillas-veltet-i-Sandviken-2854445.html [Accessed 29.04 2016].

VERYZER, R. W. 1998. Discontinuous innovation and the new product development process. *Journal of product innovation management,* 15**,** 304-321.

WALSH, S. T., KIRCHHOFF, B. A. & NEWBERT, S. 2002. Differentiating market strategies for disruptive technologies. *Engineering Management, IEEE Transactions on,* 49**,** 341-351.

WANG, F., TAMURA, Y., YOSHIDA, A. & OKADA, R. 2012. Wind force characteristics of scaffoldings with sheets.

WIKGRUPPEN. 2016. *Om Wik Gruppen* [Online]. Available: http://www.wikgruppen.no/no/wik-gruppen/ [Accessed 27.04 2016].

WILSON, J. S. 2004. *Sensor technology handbook*, Elsevier.

YIN, R. K. 2013. *Case study research: Design and methods*, Sage publications.

ØSTRING, J. L. H., MORTEN RYDLAND;

PEDERSEN, TORD OLANDER;

MONSEN, ØISTEIN NORUM. 2013. *Stillas kollapset og traff eldre mann i hodet* [Online]. Nordlys. Available: http://www.nordlys.no/nyheter/stillas-kollapset-og-traff-eldre-mann-i-hodet/s/1-79-6775560 [Accessed 11.05 2016].

8. Appendix

Intervju-guide

1. Oppvarming (20 min)

1.1. Innledning

1.1.1. Personlig introduksjon

1.1.2. Fortelle kort om prosjektet *(stillas og sensorteknologi)*

1.1.3. Fortelle litt om poenget med intervjuet *(Markedsundersøkelse / kunnskapsinnhenting)*

1.2. Formaliteter

1.2.1. Transkribering *(Tillatelse for lydopptak?; evt. gi korrespondenten kontroll)*

1.3. Eksempel

1.3.1. Har du noen opplevelser/eksempler der det har skjedd sikkerhetsmessige problemer i forbindelse med bruk av stillas?

1.4. Innføringsspørsmål

Stillas utfordringer / forbedringer

1.4.1. Hva føler du er de største sikkerhets baserte utfordringene i dagens stillasindustri?

1.4.2. Har det skjedd noe forandringer eller framsteg de siste årene innen sikkerhetsrutiner eller teknologi innen stillas bransjen som du vet om?

2. Hoveddel (30 min)

Markedet

2.1.1. Hvilke konkrete forbedringer føler du ville vært viktig for stillasbransjen?

(Begrunne hvorfor og hvor viktig de er)

2.1.2. Hvis du måtte gitt forslag til enkle og effektive løsninger på utfordringene, hvordan ville disse sett ut?

(Kan være både teknologier, rutiner, regelverk osv.)

Produktet

2.1.3. Hva er inntrykket av produktforslaget vårt og hvilke fordeler / ulemper ser med produktet?

(Kan handle om implementering, det tekniske, det praktiske osv.)

2.1.4. Hvis du skulle forbedret produktideen våre, hva ville du da ha foreslått?

Implementering

2.1.5. Hvordan tror du det hadde vært best å implementere produktideen vår?

(operatører, produsenter, bedriftene / som integrert teknologi eller separat service)

3. Avslutning (15 min)

3.1. Avsluttende spørsmål

Personlig mening

3.1.1. Tatt alt i betraktning, ser du et bra markedspotensial i produktideen vår? Hvilke fordeler ser du for deg?

(Begrunnelse / hvorvidt en kunne brukt produktet)

3.1.2. Ville du selv vært interessert i bruken av produktet?

3.2. Kontakt/avslutning

3.2.1. Er det noen andre du føler vi burde snakke med om dette?

3.2.2. Er det noe annet jeg burde ha spurt eller vite i forhold til det som har blitt diskutert?

3.2.3. Er det mulig å få en mail adresse/telefonnummer for eventuell kontakt og påfølgende spørsmål?

Takk!