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Construction cost of timber buildings

Funded by the COWI-fund

Arkitema COWI CHALMERS UNIVERSITY OF TECHNOLOGY

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A study comparing construction cost of CLT buildings and concrete buildings in the Scandinavian countries.

Funded by the COWI-fund

Prepared by:

Arkitema K/S
Ny Carlsberg vej 120
DK-1799 Copenhagen

COWI A/S
Karvesvingen 2
NO-0579 Oslo

Chalmers University
Chalmersplatsen 4
SE-412 96 Gothenburg

Julie Hansted Andersen, Arkitema DK
Michael Englund, Arkitema SE
Yutaka Goto, Chalmers University SE
Ketil Armann Hansen, COWI NO
Henning Johansen, COWI NO
Daniela Grotenfelt, Arkitema SE

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Preface

This report is a result of a development project funded by COWI-fund. We want to thank COWI-fund for the possibility to do this project, and the willingness to support the agenda of timber buildings based on facts and well-studied data. With this report we want to share more knowledge of timber buildings and therefore this report is meant to be distributed to all who wants to know about cost of buildings with CLT as the load-bearing system. This is as well the agenda for COWI-fund.

The project is a collaboration between Arkitema, COWI and Chalmers University of Technology where the different competences from academia, engineering and architectural knowledge have complemented each other and been a great teamwork.

In addition to the main team from Arkitema, COWI and Chalmers, stakeholders have been included in the project by delivering case study material, interviews and advise for the project. A special thanks to the companies; Solid, VEF, SJB bygg, Bengtsforshus, Växjöbostäder and Titana for the time and willingness of letting us use cost data from their projects. This has made it possible for us to perform the analysis of actual cost data and thereby gain more knowledge within the subject.

Also, a special thanks to Olivia Thim from the city of Växjö, Carina Herbertsson and Maria Dahl from Växjöbostäder, Jakob Kock from Adserballe & Knudsen, and Erlend Dragesæt from Veidekke byg for the participation of interviews and the willingness to share their experience of CLT buildings. This have given the project new knowledge and has contributed with nuances which cannot be analysed directly from cost data.

The report starts with some background information of why the project have been important to conduct and seek knowledge of which potentials CLT have for the construction industry. This is followed be the aim and the limitations of the project, and hereafter the methodology is described for the project. After the methodology the results of the literature study is presented with the state-of-the-art within the subject. Thereafter the results of the case studies and interviews are presented. The results of the case studies and interview establish the analysis of the project and forms the foundation for the discussion which is followed by the results in the report. Through the discussions the uncertainties of the project are presented and discussed, as well as the potential market developments which might occurs in relation to focus of decreasing the GHG level. In the end of the report the conclusions from the analysis and discussion are summarized. The conclusions are listed as short take-aways for the entire project.

We hope that the report will be read with interest and raise the curiosity for further studies within the subject of cost of timber buildings.

Abstract

There are increasing interests and practices in modern large timber constructions globally for the renewability and carbon storage function of wood. However, many stakeholders with limited knowledge and experience with timber still feel uncertain on how to carry out construction projects with timber. The common notion is that timber constructions would become more costly than a conventional alternative such as concrete. In order to inform wide spectrum of construction stakeholders in Scandinavia, this report presents a study on construction cost of cross laminated timber (CLT) buildings compared with concrete/steel buildings in Denmark, Norway and Sweden.

The study investigated the actual cost of 9 recent multi-storey residential buildings, 5 constructed with a load-bearing system in primarily CLT and 4 constructed in primarily concrete in Norway and Sweden. Due to the nature of the chronological and geographical differences of market conditions, the cost data were evaluated separately for Norway and Sweden.

In addition to the case building analysis, interviews were conducted with stakeholders from the case building projects as well as those from the industry with experiences with CLT buildings. The interviews contributed to a broader perspective of the cost analysis, with explanations of the projects and experiences of advantages and disadvantages for CLT building and concrete buildings.

The results showed a tendency that the construction cost of the Norwegian CLT projects were higher than the Norwegian concrete projects. For the Swedish projects the concrete building had a higher cost compared to the CLT projects, however it can't be concluded as a tendency for the Swedish projects, since investigation only included one concrete project and two CLT projects.

The results showed that often the material-related costs were higher for CLT buildings than concrete buildings. Such costs are for example the material cost itself and transportation cost for a long distance. Furthermore, the fire protection and measures for the finalized building according to fire safety resulted in a higher cost in the CLT cases. However, the construction time is often shorter for CLT buildings than concrete buildings, and CLT buildings are lighter and therefore the foundation can be dimensioned smaller. Although such observations were made, throughout the interviews it was stated that one should be careful comparing the cost of two buildings since the cost is very much depended on the specific project. Thus, the results shown in this report must be seen as tendencies and not as a forecast for specific cost difference between CLT building and concrete buildings.

This study was an investigation of construction costs and advantages and disadvantages of CLT buildings in relation to the construction cost up till 2022. When there is a major change in the

economy and legislations of the construction sector, the cost structure may be substantially affected. One of such factors may be the increasing focus on the reduction of greenhouse gas (GHG) emissions from the construction industry. The availability of resource might be also a key factor for the future cost development for both CLT and concrete.

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1. Introduction

1. Introduction

1.1 Background

In a time when population grows, the need for the building mass increases. Currently, this global trend of continuous growth in population and urbanization is resulting in higher concentration of greenhouse gasses (GHG) in the atmosphere. For the transition to a more sustainable society, the GHG concentration must be decreased to slow down and eventually cease the global warming. In the global scale, the construction industry is responsible for 37% of GHG emissions[1], and it is one of the key sectors to take drastic actions for the transition to a less carbon intensive industrial ecology. Therefore, there is an increasing need for technical solutions in construction industry to decrease the GHG emissions.

When considering the application of a more environmentally friendly technology, one must consider its economic aspect as well in order to practically succeed in reducing the GHG emissions. In the practices of construction projects in the current market, decisions are very often made based on the priority on the economic performance among all viable technical alternatives. This is because construction projects must satisfy numbers of legislative requirements for safety, comfort, energy efficiency, etc., and this incurs already a large cost in general even in the case of solution with the lowest possible cost.

Yet, there is an increasing number of applications of more sustainable and costly solutions in the construction industry. This is especially the case when those technologies directly concern the energy efficiency of the buildings, such as thicker insulation, heat exchanger, better-insulating window, etc. This trend is primarily driven by both environmental and economic views. While the solution may be more environmentally, the saving of energy over a certain period can compensate the higher initial investment. This payback time analysis is key to promote those energy efficiency measure in many cases.

However, in the case of embodied carbon emissions of construction materials, there is no tangible payback time for different levels of investment unless some substantial carbon tax rules would be introduced in the market. The current market situation does not economically favour a less carbon intensive material unless it is less costly than other common materials.

[1] UN Environment Program. 2021 GLOBAL STATUS REPORT FOR BUILDINGS AND CONSTRUCTION - Towards a zero-emissions, efficient and resilient buildings and construction sector. 2021.

In the recent years, wood is obtaining higher and higher interest in the construction sector. Wood is a renewable material which sequesters carbon from the atmosphere and stores it in the wood material itself until it is burned or chemically/biologically decomposed. Reuse of the timber building will delay the return of carbon to the atmosphere. Among various wood products from all industries, constructions are supposed to have a rather long service life. This means that while the wood materials as construction timber increase in the global building stock over a long period of time, forests can grow and continue sequestering the atmospheric carbon. As long as construction timbers come from sustainably managed forests, the increase of timber construction means the increase of carbon stock in the building stocks. When those timber replaces other more carbon intensive materials such as concrete and steel, it is expected to reduce the carbon emissions from the construction industry. Furthermore, the process of harvesting and timber production has lower CO_2 emissions compared to conventional concrete and steel.

Since the revision of the fire safety regulations in various countries in the past decades, modern and large timber constructions have been emerging. For example, in Sweden, the fire regulation was revised in 1994, which allowed timber constructions to be 3 storeys or higher and this was the turning point for the Swedish construction industry. The share of wood constructions in newly built multi-story apartment in Sweden is estimated at around 20% in 2021. This is a significant change considering that it was 0% until the legislative change, and the market trends shows that it would increase even further.

The major drivers of this significant growth of the timber construction industry in Scandinavia, especially Norway, Sweden and Finland, are; (1) there are large areas of productive forest and thus there are sufficient resources for the local market, (2) there are well-experienced wood-processing and timber construction companies since timber construction has been very common for smaller buildings, and (3) there is the growing consciousness of environmental sustainability and timber is seen as a more favourable option for its carbon neutrality, renewability and circularity.

In the past years, the global record of height of modern timber constructions is frequently renewed (Treet[2] in Bergen (Norway) with 52.8 m in 2015, Brock Commons[3] in Vancouver (Canada) with 54

[2] Treet – *a wooden high-rise building with excellent energy performance*, https://www.buildup.eu/en/practices/cases/treet-wooden-high-rise-building-excellent-energy-performance, 04 january 2017

[3] *Operational performance of cross laminated timber: Brock Common Tallwood House*, https://sustain.ubc.ca/sites/default/files/UBC%20Brock%20Commons%20Structural%20Performance%20Report%20Sept%202020.pdf, University of British Columbia, Sustainability, September 2020

m in 2017, Mjøstårnet[4] in Brumunddal (Norway) 85.4 m in 2019). This exemplifies the growing global trend of the timber construction industry.

This advancement of the timber construction industry is primarily supported by research and developments in structural and fire safety technologies. Among various technologies, cross laminated timber (CLT) has been a major contributor of the expansion of the technical possibilities especially in structural capacity[5]. CLT is a multi-layered glued timber panel. Each layer consists of timber lamellas laid in the same direction, and each neighbouring layers are glued crosswise. CLT was invented in 1990's, and its versality on the dimension of structural panels and the high loadbearing capacity has driven wood-processing companies globally to invest in own CLT production facilities. There are various structural advantages of CLT compared to other wood-based construction components: (1) It has a high loadbearing capacity, (2) the structural planning is relatively simple and similar to concrete structure, and (3) it has a higher dimensional stability under varying humidity conditions compared to solid wood.

Although there are increasing interest and practices in modern large timber constructions, many stakeholders (municipality, building owner, developer, contractor, architect, engineer, consultant etc.) with limited knowledge and experience with timber still feel uncertain on how to carry out construction projects with timber. One major concern is the economic aspect of the projects. The common notion is that timber constructions would become more costly (or less predictable) than a conventional alternative such as concrete.

1.2 Aim and limitation of the study

This study aims to analyse construction cost of timber buildings and to discuss the advantages, disadvantages and potential of cost optimization in comparison to concrete alternatives.

The study investigated the actual construction cost of multi-story residential buildings whose primary loadbearing structure is made of CLT in Norway, Sweden, and Denmark. A specific typology of building (multi-story residential) with a specific material (CLT) was chosen in order to make the collected data more comparable to each other. Multi-story residential building was chosen because this is the most common and relevant building typology with regard to urban densification and sustainability impacts. CLT was chosen in order to make the cost analysis more

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[4] R. Abrahamsen, *Mjøstårnet - 18 storey timber building completed. Proceedings of International Holzbau-Forum*, Garmisch Partenkirchen. 2018.

[5] R. Brandner et al. *Cross Laminated Timber (CLT): overview and development. European Journal of Wood and Wood Products*, vol.74, pp.331–351. 2016.

comparable to conventional concrete buildings in relation to stability and load-bearing structure for multi-story buildings.

The cost data analysis and comparison were carried out in a simplified manner, not applying a full life cycle cost (LCC) analysis. This was decided since a full LCC would demand to obtain the information of all materials, their costs and their life span for all the case buildings. It was assessed to become unreasonably intricate to collect full sets of data for all cases analysed. The data for a full LCC would include too much missing information in the calculations and thereby there would be a risk of incomplete and misleading results.

The investigation was limited to the cost of the design and construction stage (A1-A5 module, according to the Life Cycle Stages of EN 15978:2011[6]) until the project is handed over to the occupants. Only the actual construction cost was investigated, and the sales price and other sales-associated factors of the apartments is not included. Furthermore, literatures[7, 8] shows that if a timber construction is fully protected against weather, the lifespan of the construction will be the same as for a conventional concrete construction. Thus, it was assumed that the maintenance cost for the load bearing frame was zero in both CLT and concrete cases during a calculation period of 50 years. The operational cost for heating etc., was assumed to be the same between CLT and concrete cases with the same energy performance and appliances installations. The demolition phase was excluded as CLT constructions are still new in the market and there is little practical experience in the demolition of CLT apartments.

In addition, this report does not present environmental performance (ex. GHG emissions) of the case studies, as this was not the focus of this study.

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[6] SS-EN 15978:2011. *Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method*.
[7] S. Liang et al. *Life-cycle cost analysis of a mass timber building – methodolody and hypothetical case study*, USDA, 2019
[8] Waugh Thistleton Architects, *100 Projects UK CLT*, Waugh Thistleton Architects, 2018

2. Methodology

2. Methodology

The present study was conducted by performing (1) a literature study on cost aspects of CLT constructions and (2) analysis of the actual cost of six case buildings from Norway and three case buildings from Sweden. Furthermore, in order to complement the understanding and insights from the literature study and case study analyses, interviews were performed with the building owners and contractors of the case studies as well as other stakeholders within the industry.

2.1 Literature study

The aim of the literature study was to investigate the state-of-the-art research of the cost of timber projects. By examining previous studies about the topic, their results can serve as reference for the results of present study's case study analyses and interviews. As a literature study uses second-hand data and case studies deliver first-hand data, the study opens for a wider perspective of results for the study.

The literature study has been conducted as a systematic review of academic papers and reports.

2.2 Case study

A case study represents the actual problems and benefits which might occur during the design stage and construction stage of a project. By using case study as first-hand data it enables to examine the data more deeply in a specific context, which is for multi-story residential buildings in the Nordic countries for this study. This specifies the results of the study to actors in the construction industry in the Nordic countries and creates a more detailed insight into the subject of interest for these actors.

However, case study research has its limitations. The results based on a case study are only as good as the data is and the method is as well criticized for generalizing results based on limited number of cases. Yet, case study is useful to explain a process and the result of the studied subject by using both the quantitative and qualitative data for real-life projects. Hence, case study is chosen as the primary method for this study. These case studies are examined during qualitative interviews and quantitative data analyses.

2.2.1 Collecting data for case studies

Before choosing the case buildings and collecting data, limitations were set in order to obtain data with sufficient quality and comparability.

The types of case studies were limited to multi-story residential buildings constructed in CLT and conventional concrete and steel in Denmark, Sweden and Norway. The building should have at least three storeys in some parts of the building and a maximum of eight storeys. For the timber building the primary the loadbearing system should be constructed in CLT. Furthermore, it was prioritized to use case buildings which were built by contractors who have built such types of buildings before. This was for minimizing additional cost as a result of developing new construction methods and larger beginner mistakes. It was identified in previous studies that cost might increase when the contractor is doing a CLT project for the first time [9] [10]. In addition, projects with a turnkey contractor were preferred, to have a stronger comparability between the projects.

With these limitations in mind, contractors and building owners in Denmark, Norway and Sweden were contacted and asked if they were willing to share cost data of the actual cost from the design stage to finished construction (A1-A5). However, it was found that the numbers of multi-story residential buildings with at least three storages are limited in Denmark. Thus, it was not possible to include any Danish projects for the case studies.

All contractors and building owners were asked to provide the construction data in the same cost group structure to ensure comparability. The construction cost data was collected in accordance with the cost structure model in the Norwegian Standard (NS) 3451 "Bygningsdelstabell (Building component table)". Table 1 shows the structure of the cost items and how the data was delivered. If the contractors or building owners were not able to deliver the cost data according to the standard, they were asked to deliver the total cost sum of the project. It was decided to include these projects with limited level of detail in order to increase the amount of case buildings. However, these projects were excluded from the comparison of each cost group and only used for comparison of the total cost.

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[9] D. Bylund, *A cost comparison between multi-residential prefabricated timber frame and precast concrete construction, Forest & Wood products Australia*, 2017

[10] R. E Smith et al., *Mass timber: evaluating construction performance, Architectural engineering and design management*, 2017

Table 1 - Cost group structure according to NS 3451

	Cost group	Cost (not index regulated)
01	Common cost	
02	Building	
021	Building materials, general, demolition, prepare work for the build	
021	Foundation, groundwork	
022	Load bearing structure	
023	External walls, thermal envelope	
024	Inner walls	
025	Decks	
026	Outer roof	
027	Fixed inventories belonging to the building itself	
028	Stairs, balconies	
029	Support service plumbing and ventilation	
029	Support service electrics	
03	Plumbing and ventilation	
04	Electricity	
05	Telecommunication and automation	
06	Other installations	
	Total construction (01-06)	
08	General costs	
	Total project (01-08)	

In addition, the contractors and building owners were asked some questions to clarify the project scope. Table 2 below shows those questions.

Table 2- Questions about project information and key numbers of the case studies

Project information and key numbers	
Construction period	
Name of project	
Massive timber or concrete building	
Type of building (residential, care homes, hospital, student housing)	
Address	
Number of storages	
Gross total area (GTA)	
Useable area (BRA)	
Parking (GTA)	
Number of apartments	
Size of apartments (average m^2)	
Description of construction technique and load bearing system	
Handling of moisture under construction period – Did you use any cover? Drying?	
Ground conditions and type of foundation	
Share of GTA which is constructed in massive timber. (E.g. building with cellar in concrete)	
Drawings that accompany the building application (Plan, sections, and facades)	
IFC-model	
Form of company	
Supplier of massive timber	
Energy use or energy class	
Collaboration with Swedish supplier?	
Free text, useful information about the construction.	

Table 1 shows that cost data was collected as a total cost of the project, but in order to analyse the cost data and compare the case projects it is chosen to divide the cost pr. Gross Total Area (GTA). However, it is important to define what is included in GTA in Norway and Sweden.

GTA is defined by all the area on each floor including the thermal envelope. Glazed balconies are included in the Swedish and Norwegian GTA, however none of the case studies in this project has glazed balconies. When the roof is pitched, the area is counted from where the perpendicular line to the floor is 1.9 m high to the roof. See Figure 1 below where the blue area shows the GTA.

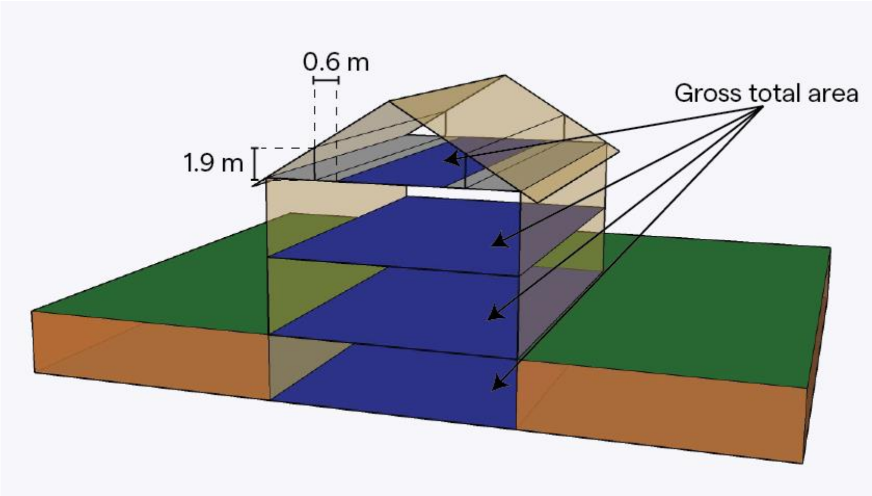

Figure 1 - Gross Total Area. The blue area shows the GTA.

2.3 Interviews

Qualitative analyses have been performed as interviews of developers and entrepreneurs of the case project and of other stakeholders within the building industry. The interviews can collect insights into behaviours and thoughts which quantitative data cannot. It can as well explain the reason for the data to occur in a specific way.

The interviews were performed as semi-structured interviews with the ability to be flexible from the planned questions and to be creative with more questions, which come throughout the interview. The planned questions were provided to the interviewees in writing in advance. In some cases, response was collected in writing, which was complemented by an oral interview to ask further questions afterwards. This method was useful for the project since the people interviewed were able to speak of their experiences. Table 3 shows the interviewed people.

Table 3 - Interviewed people

Interviewed	Country	Company and position
Olivia Thim Carina Herbertsson Maria Dahl	Sweden	City of Växjö, business developer Växjöbostäder, project manager Växjöbostäder, former staff
Jens Hagelberg	Sweden	SJB Bygg, Calculation/Project/purchase manager
Wojciech Wondell	Sweden	Titania, project manager
Richard Hansen	Norway	Solid, Calculation manager
Petter Pallesen	Norway	VEF, Project- and property manager
Erlend Dragesæt	Norway	Veidekke byg, Project manager
Jakob Kock	Denmark	Adserballe & Knudsen, Technical director
Carl Petterson	Sweden	Red Fire Engineer Sweden AB, Fire engineer

3. Results of literature study

3. Result of Literature study

The cost of timber building compared with concrete or steel building alternative has been investigated in past studies. In this literature study, the results of the various studies were compared as the state-of-the-art of the topic. It also aimed to compare their results to the results of present study's case studies. The following sections summarize the data on (1) project period and cost and (2) advantages of disadvantages of timber constructions.

3.1 Project period and cost

The period for the design and construction stage (project period) has a great impact on the total construction cost of a building, hence it has been examined in different comparative studies of traditional concrete/steel buildings and timber buildings. Table 4 shows the results of project period and cost for five different studies comparing concrete/steel and timber buildings.

Table 4 - Comparisons of time and cost of timber building compared to concrete/steel alternative in five different studies.

Articles	**Construction time of timber buildings compared to concrete/steel building [+/- % time]**	**Project period of timber buildings compared to concrete/steel building [+/- % time]**	**Cost of timber buildings compared to concrete/steel building [+/- % cost]**
M.F. Lagurda-Mallo (2016)[11]	-61,1%	N/A	-21,7%
R. E. Smith (2017)[12]	N/A	-20%	-4,2%
Centre for Sustainable Architecture with wood (2016)[13]	+20%	N/A	+4%
Østnor (2018)[14]	-42%	N/A	+60%
Halseth (2019)[15]	-40%	N/A	+13%

The results in Table 4 show a varying result of the project period and cost, but most of the examined studies have a shorter construction time for the timber building. The only study with a longer construction time for the timber building was in the article *Centre for Sustainable Architecture with wood*[13]. The reason for this study having a longer construction time was that the timber building was constructed as a prefabricated timber frame structure, which was stated to have a longer construction time compared to panel system in concrete. Meanwhile, the other studies, which all showed a shorter construction time in the timber case, compared CLT with

[11] M.F. Lagurda-Mallo. *Cross-laminated timer vs. concrete/steel: cost comparison using a case study*, 2016.
[12] R. E. Smith. *Mass Timber evaluating construction performance*, 2017.
[13] Centre for Sustainable Architecture with wood. *A cost comparison between Multi-Residential Prefabricated Timber Frame and Precast Concrete Construction*, 2016.
[14] Østnor. *Massivtre og Plasstøpt betong: en casestudie*, 2018.
[15] Halseth. *Boligbygging I massivetre: Sammenligning av boligblokk I massivtre og betong*, 2019.

concrete. Furthermore, the timber frame construction in *Centre for Sustainable Architecture with wood* [13] was supposed to receive 5 Star grading of the Australian sustainable building certificate, Green Star[16], which was not the case for the compared concrete building. The certification system required more documentation and additional tasks, thus the process extended the construction time additionally.

One of the reasons for higher cost in three of the examined studies was due to the higher material prices for timber compared to concrete[13, 14,15]. Another reason is that the cases in those studies (with CLT or prefabricated timber frames) were pilot projects, which resulted in more working hours for the design team to create solutions for e.g., acoustic and fire.

The Swedish company, ETC, who develops, finances and built timber buildings, describes how they have developed construction and design methods and thereby decrease the cost. After building three buildings they have seen that their second building was 9% less expensive in labour costs. The third building was 10% less in labour costs than the second building. They observed this despite of the fact that during this time the labour costs in general had risen substantially[17]. It shows an example of the cost reduction potential in learnings from the experiences for further process optimization.

Another study presented in the book "*100 projects UK CLT*" investigated the timber assembly time, total construction time and the construction cost of 100 timber building projects in the UK[18]. The average assembly time, average construction time and average construction cost pr. m^3 of the cases from this book was calculated by dividing the data of examples for various building types and structural type. The results are presented in Table 5.

[16] Green building council Australia, *What is green star?*, https://new.gbca.org.au/green-star/exploring-green-star/
[17] ETC bygg, *Ekonomin for vara forsta hus*, https://etcbygg.se/bygg/ekonomin-for-vara-forsta-hus/, 7. december 2021
[18] Waugh Thistleton Architects, *100 projects UK CLT*, Waugh Thistleton Architects 2018

Table 5 - Average timber assembly time, construction time and construction cost pr. m3. Results are divided in building type and structure type (calculated based on the data in (Architects, 2018))

	Sample size	Timber assembly pr m^3	Total construction time pr m^3	Construction cost pr m^3
	pc	weeks /m^3	weeks /m^3	£/m^3
Educational	32	0.0119	0.030	5724
Residential	32	0.00714	0.092	8356
Commercial	15	0.0109	0.088	17566
Public and civic	21	0.0153	0.198	26996
Only CLT	38	0.0107	0.083	12759
Other timber componence than CLT	32	0.0105	0.087	12036
Hybrid	30	0.0105	0.085	10066

Results in Table 5 do not show a direct correlation between having a shorter timber assembly time and having a lower construction cost. However, it shows correlation between a short total construction time and a lower construction cost. Furthermore, the results show that assembly time for only CLT, other timber components than CLT and hybrid is nearly the same. This also applies for the total construction time of the three structure types.

3.2 Advantages and disadvantages

In addition to the investigation on the project period and cost of timber buildings, the literatures also examined other advantages and disadvantages in a qualitative manner. Table 6 and Table 7 show the list of advantages and disadvantages of timber constructions discussed in each literature, respectively.

Through the advantages and disadvantages described in Table 6 and Table 7, it showed that shorter constructions time is mentioned in 5 out of the 6 investigated articles as an advantage of timber buildings. However, 5 out of the 6 articles mentioned that a more expensive design stage was a disadvantage for the timber constructions compared with concrete buildings. As well the codes and permits for at timber building was mentioned as a disadvantage for timber buildings in 5 of 6 articles. But all 6 articles mentioned that reducing CO_2 emissions was an advantage for the timber buildings.

Furthermore, the literature study showed that the state-of-the-art literature has different focuses and has experienced different advantages and disadvantages. This means that by constructing a timber or a concrete building the project would not meet all the same advantages and disadvantages. But the literature study also illustrates that not many investigations have been conducted of real-life cases comparing the cost of timber constructions and traditional concrete constructions.

Table 6 - Advantages of applying timber as the structural material reported in different literature. The x marks which literature has mentioned the subject as an advantage in their report.

Advantages mentioned in the literature.	M.F. Lagurda-Mallo (2016)	R. E. Smith (2017)	Centre for Sustainable Architecture with wood (2016)	Østnor, (2018)	Halseth (2019)	Architects (2018)
Reduced CO2 emission	x	x	x	x	x	x
Off-site construction		x	x			x
Added value with lower quality of timber for CLT		x				
Speed	x	x		x	x	x
Quickly a closed envelope		x		x		
Labor cost and manpower	x	x			x	x
Lower weight and thereby smaller foundation	x	x	x			x
Precision		x				x
Health and safety on-site		x		x	x	x
Cost	x	x				
Design and flexibility						x
Seismic activity	x					x
Cascading possibilities						x
Less waste on-site						x
Less transportation due to lighter material						x

Table 7 - Disadvantages of applying timber as the structural material reported in different literature. The x marks which literature has mentioned the subject as a disadvantage in their report.

Disadvantages mentioned in the literature.	M.F. Lagurda-Mallo (2016)	R. E. Smith (2017)	Centre for Sustainable Architecture with wood (2016)	Østnor (2018)	Halseth (2019)	Architects (2018)
Expensive design stage		x	x	x	x	x
Lack of information		x	x	x	x	
Logistics		x				
Acoustics and vibration		x		x	x	
Code and permits	x	x		x	x	x
Fire				x	x	x
Wind concerning cranes		x				
Planning		x		x		
Total cost			x	x	x	
Architects and client's attitude towards timber	x					
Water and moisture				x	x	x

4. Results of case study and interview

4 Results of case study and interview

4.1 Collected case buildings

This section describes the 9 case buildings (6 projects in Norway and 3 projects in Sweden) for the analyses in the project.

4.1.1 Bergheim bo- og aktivitetssenter (CLT 1)

Bergheim bo- og aktivitetssenter (CLT 1) is a care home for 96 residents located in Halden in the south of Norway. The GTA of the building is 11,700 m^2, with above ground parking only. The building is distributed on three storeys. The upper two storeys were constructed in CLT and the ground floor in concrete. The building is shaped in a horseshoe form with a yard in the middle. The rendering and the completed project are shown in Figure 2.

The building was constructed in the period from October 2017 to February 2019 by a turnkey contractor, Solid Entreprenør. The building owner is Halden municipality. The municipality specifically demanded a massive timber building for the care home, and thus the project was planned to be a timber building from the beginning. The supplier of the CLT was Binderholz located in Austria.

Figure 2 - Bergheim bo- og aktivitetssenter project (CLT 1) constructed with CLT in Hadlen, Norway

4.1.2 Solhøy (CLT 2)

Solhøy (CLT 2) is a care home for 67 residents located in Vestby in the south of Norway. Solhøy has four storeys. The basement is constructed in concrete and steel, and the above three storeys are constructed in CLT. The building has a GTA of 11,536 m^2 including parking basement, with an average apartment size of 33.5 m^2. The construction of the building started the January 2021 and is planned to end in December 2022, thereby the project is still under construction. However, the project has a turnkey contractor with a fixed price for the total cost of the building. The contractor is

Solid Entreprenør, which is the same company for CLT 1. The building owner is Vestby municipality, who demanded a building constructed in massive timber from the beginning. The supplier for the CLT panel is Splitkon, located in Norway. Figure 3 shows how the building is planned to become and the status of the construction in Mars of 2022.

Figure 3 - Solhøy project (CLT 2) constructed with CLT in Vestby, Norway

4.1.3 St. Olavsvej 18 (CLT 3)

St. Olavsvej 18 (CLT 3) is an apartment building in five storeys including the basement, located in Kristiansand in the south of Norway. The GTA of the building is 1,657 m^2 including 550 m^2 parking basement and 28 apartments of average 45 m^2. The basement is constructed in concrete and the upper storeys are constructed in CLT. The construction started in 2021 and is currently under construction. Similar to CLT 2 project, this project also has a turnkey contractor, VEF Entreprenør, with a fixed price of the project. Figure 4 shows how the building is planned to become and under construction.

Figure 4 - St. Olavsvei 18 project (CLT 3) constructed with CLT in Kristiansand, Norway

4.1.4 Ski BB1 Magasinparken (Concrete 1)

Ski BB1 Magasinparken (Concrete 1) is an apartment complex, consisting of 7 buildings with 183 apartments in total, and is located in Ski in the south of Norway. The building is owned by Solon Bolig AS Solon Eiendom, and was built by Solid Entreprenør, which as well constructed CLT 1 and CLT 2. The average apartment size is 79 m^2 and the GTA of the project is 24,805 m^2, including 7,800 m^2 parking basement. The number of storeys varies for each building. Three of the buildings have four storeys, three other buildings have five storeys and only one building has eight storeys. In addition, each building has a basement. The buildings are constructed in concrete and steel, with slabs in concrete and steel columns as the loadbearing system. The foundation was made as pile foundation, which often has a higher cost. The project was constructed from March 2019 to September 2020. Figure 5 shows some pictures of the buildings.


Figure 5 - Ski BB1 Magasinparken project (Concrete 1) built with concrete in Ski, Norway

4.1.5 Trelasttomta (Concrete 2)

The project Trelasttomta consists of four apartment buildings varying from four to seven storeys and one shared basement underneath all the four buildings. The project is owned by Ekornud Eindom AS and is located in Myrvoll in the southern part of Norway. Architect of the buildings are Nuno Architects and is constructed by Solid entrepreneurs as the turnkey contractor, from January 2019 to December 2020. The total gross area for all four buildings is 9,950 m^2 including 2,250 m^2 parking basement and consists of 72 apartments with an average size of 63.2 m^2. The buildings are mainly constructed in concrete and steel, with concrete slabs and loadbearing system in steel. Figure 6 shows some renderings of the buildings of Trelasttomta.

Figure 6 - Trelasttomta (Concrete 2) constructed in concrete in Myrvoll, Norway

4.1.6 Fagertun Panorama (Concrete 3)

Fagertun Panorama consists of four apartment buildings with two or three storeys and a basement, which are made in concrete. The GTA of the project is 3,359 m^2 including 1,216 m2 parking basement with 21 apartments with an average size of 91 m^2. The owner is Dovreveien 3 AS, and buildings are located in Lillesand in the south of Norway. VEF Entreprenør was the turnkey contractors of the project and constructed the building from November 2019 to October 2021. The buildings were constructed as conventional apartment buildings of Norway with steel columns and concrete slabs. Figure 7 shows the project after construction completion.

Figure 7 - Fagertun Panorama (Concrete 3) constructed in concrete in Lillesand, Norway

4.1.7 Arken (CLT 4)

Arken consists of three buildings with total of 85 rental apartments and has a GTA of 8,327 m^2 with above ground parking only. The project was built in Växjö in the southern part of Sweden. From the beginning it was required to be constructed as a wooden construction, with environmentally friendly materials and low energy consumption. In fact, the project was planned as a part of the regional Energy Plan with a requirement of yearly energy consumptions of 55 kWh per unit heated floor area. However, this project has lower U-values for the building envelope with thicker insulation compared with buildings built according to the minimum requirement by the Swedish regulation. The buildings consist of apartments with one to five rooms, with an average apartment size of 65,3 m^2. The buildings were constructed with a CLT frame, with slabs, outer walls, load bearing inner walls, joist, balconies, elevator shafts, beams and columns in CLT and glue laminated timber from Martinssons in the north of Sweden. The buildings were constructed by a local contractor in Växjö, Värends Entreprenad. Figure 8 shows the project after the construction completion.

Figure 8 - Arken (CLT 4) constructed in CLT in Växjö, Sweden

4.1.8 Björkdungen 5 (CLT 5)

Björkdungen 5, located in Bengtsfors in the south-west of Sweden, is a four-storey apartment building with a dentist office placed on the ground floor of the building. The basement and the ground floor were made from concrete, including the elevator shaft. The load bearing structure in the two storeys above was made from CLT, including half of the facade walls. The other half of the facades was made from SJB bygg own light weight system in wood. The inner load bearing walls of the smaller top floor was from CLT. The facade walls were made from their own light weight system. The elevator shaft was made from CLT in the three top levels. The CLT was delivered from the mill of Stora Enso in central Sweden

The building is owned by Bengtsforshus AB, which is the municipal housing company in Bengtsfors. The building was built by SJB bygg as the turnkey contractor with a construction time of 15 months, from March 2020 to August 2021. This project was the first CLT building built by SJB Bygg. The GTA of the project is 1,536 m^2 including 375 m^2 for the dentist office, a basement of 166 m^2 and 11 apartments with a size of 55-76 m^2. Figure 9 shows the building Björkdungen 5 under construction and as a finished building.

 

Figure 9 - Björkdungen 5 (CLT 5) constructed in CLT in Bengtsfors, Sweden

4.1.9 Tingstorget (Concrete 4)

Tingstorget, located in Botkyrka in the south-east of Sweden, consists of 729 apartments distributed in 14 buildings varying from rowhouses in 3 storeys to multi-storey buildings with 6-8 storeys. The GTA of the whole project is 43,007 m^2 including 3,964 m2 parking basement. Tingstorget has a load-bearing system in concrete, load bearing inner walls, elevator shaft, staircase and joist constructed in steel and massive concrete. The exterior wall is made of concrete sandwich elements. The roofs are constructed with prefabricated timber elements and is covered with steel roofing plates. The contractor team was a combination between a turnkey contractor, Titania, and an executive contractor. The turnkey contractor was responsible for the framework construction and roof, and the executive contractor was responsible for the rest of the work with in-house employees as well as external consultants which might have contributed to a slightly higher cost. The total construction time was 3 years, from August 2016 to 2019. Figure 10 shows the Tingstorget buildings after the construction completion.

 

Figure 10 - Tingstorget (Concrete 3) constructed in concrete in Botkyrka, Sweden.

4.2 Analysis of cost data

The cost data for the Norwegian and the Swedish case buildings was analysed separately since the market's general economic structure and technical and legislative construction standards are not the same for the two countries.

In order to normalize the influence of the inflation and to show the magnitude of difference in the two markets, the cost data of each project was converted to euro and index regulated to prices of 2021 by the construction cost index regulation for residential buildings[19]. By converting the prices to 2021 euros it enables for comparison between the project and for future similar projects. Furthermore, all prices are presented without VAT (value added tax) and without the cost of land purchase and landscaping.

The results of the analysis of cost data are based on the raw data which was supplied by the contractors and developers. Results are strictly based on those inputs with no subjective correction of those raw data by the project team.

4.2.1 Norwegian projects

The cases *CLT 1-3* and *Concrete 1-3* are Norwegian buildings, and they were analysed and compared to each other in the same analysis. The collected data is divided into the cost group structure according to the Norwegian Standard NS 3451 "Bygningsdelstabell (Building component table)", which is presented in Table 8 and the total construction cost of the Norwegian projects are illustrated in Figure 11. The landscaping cost was excluded in these results, since the cost of landscaping is not relevant for the cost of the building in terms of the selection of the construction materials.

[19] Danmarks statistik, *Index of production in construction*, https://www.dst.dk/en/Statistik/emner/erhvervsliv/byggeri-og-anlaeg/indeks-for-byggeri-og-anlaeg, 21.06.2022

Table 8 - Results of Norwegian case projects divided into the cost group structure according to NS 3451

		CLT 1	CLT 2	CLT 3	Concrete 1	Concrete 2	Concrete 3
		EUR/GTA 2021	EUR/GTA 2021	EUR/GTA 2021	EUR/GTA 2021	EUR/GTA 2021	EUR/GTA 2021
01	**Common costs[1]**	251.29 €	678.95 €	232.21 €	308.62 €	189.77 €	161.07 €
02	**Building**	1,302.46 €	1,561.19 €	1,572.98 €	1,232.19 €	1,105.01 €	865.24 €
021	Site preparation	16.29 €	0.00 €	0.00 €	0.00 €	1.36 €	0.00 €
021	Ground and foundation	139.54 €	218.55 €	383.90 €	195.40 €	128.75 €	118.99 €
022	Load-bearing system	19.72 €	33.68 €	139.47 €	14.66 €	-	58.64 €
023	External walls	167.37 €	335.33 €	244.23 €	186.06 €	152.05 €	288.67 €
024	Internal walls	424.02 €	389.01 €	277.48 €	281.45 €	250.59 €	61.03 €
025	Slabs	222.68 €	284.38 €	176.80 €	299.59 €	392.80 €	180.01 €
026	Roof	103.35 €	116.24 €	51.62 €	37.76 €	43.17 €	55.61 €
027	Fixed furniture	147.31 €	144.15 €	97.06 €	87.80 €	73.32 €	36.10 €
028	Stairs. balconies.	17.55 €	24.19 €	166.78 €	111.42 €	51.93 €	60.44 €
029	Structural relief work - Plumbing	44.64 €	15.66 €	7.81 €	18.05 €	11.05 €	1.59 €
029	Structural relief work - Electrical	0.00 €	0.00 €	27.85 €	-	-	4.15 €
03	**Plumbing**	350.16 €	359.56 €	350.30 €	226.24 €	210.86 €	122.96 €
04	**Electrical**	181.71 €	264.25 €	140.81 €	138.53 €	117.00 €	52.07 €
05	**Telecommunications and automation**						
06	**Other installation**	17.92 €	26.80 €	256.60 €	16.70 €	23.57 €	151.18 €
	Total building cost (01-06)	2,103.53 €	2,890.75 €	2,552.90 €	1,922.28 €	1,645.69 €	1,352.53 €
08	**General costs[2]**	199.78 €	162.85 €	0.00 €	68.94 €	65.45 €	21.89 €
	Total Construction cost (01-08)	**2,303.32 €**	**3,053.59 €**	**2,552.90 €**	**1,991.22 €**	**1,711.13 €**	**1,374.42 €**

[1] Common cost includes dismantling and setup of construction site, cranes, barracks and operation of construction site, insurance, collateral and guarantees.
[2] General cost are engineering and the client's administration. project management, constructions management, special consultants (legal, financial, etc).

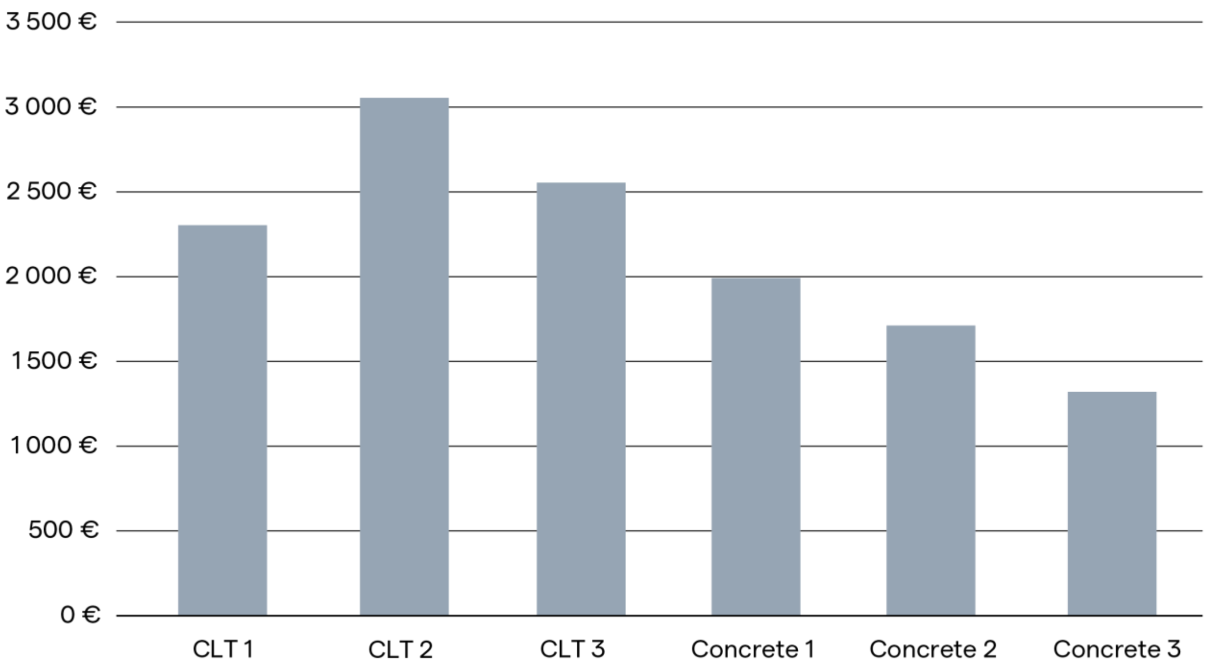

Figure 11 - Total construction cost pr. GTA for the Norwegian projects

Table 8 and Figure 11 shows that all the Norwegian concrete project has a lower construction cost compared with the CLT building. Thereby this is a clear tendency for the analysed Norwegian project, that it is more expensive to construct CLT buildings compared with CLT buildings.

However, Table 8 shows that the cost of each project can vary for each cost group. When looking into the cost group, *common cost,* it shows that the cost for CLT 2 was more than two times higher than for the other projects. Furthermore, the cost of *General cost* is three times higher for CLT 1 and CLT 2 than for Concrete 1, Concrete 2 and Concrete 3. This might show, together with the literature study, section 3.2, that there is a tendency that the CLT buildings have higher cost in the design stage than concrete buildings. However, the *General cost* for CLT 3 is not shown explicitly but is included implicitly among the other cost groups. This is a typical example of the cost calculation practice that even though the cost is divided according to the Norwegian standard NS 3451, the calculators of each project can objectively allocate the cost figures to different cost groups. This is as well shown for the *load-bearing system* of Concrete 2, where no cost is shown for this cost group, but is implicit included in some of the other cost groups. Due to this, the figures of each cost group most only carefully be compared directly and cannot be compared without knowing the background of the numbers.

In the investigation on the cost of CLT buildings compared to concrete buildings, it is necessary to exclude the cost of building parts which are not directly related to building being a CLT or a concrete building. Such building parts are the fixed furniture and installations. The costs of these groups are more dependent on if e.g., the building needs more ventilation according to its particular usage or has many small apartment units (care homes) where each unit has its own bathroom and kitchen. This increases the cost of these groups but is not related to it being a CLT or concrete building. Therefore, the cost of *Fixed furniture, Structural relief work – Plumbing, Structural relief work – Electrical, Plumbing, Electrical, Telecommunications and automation, and Other installations* are excluded in Figure 12.

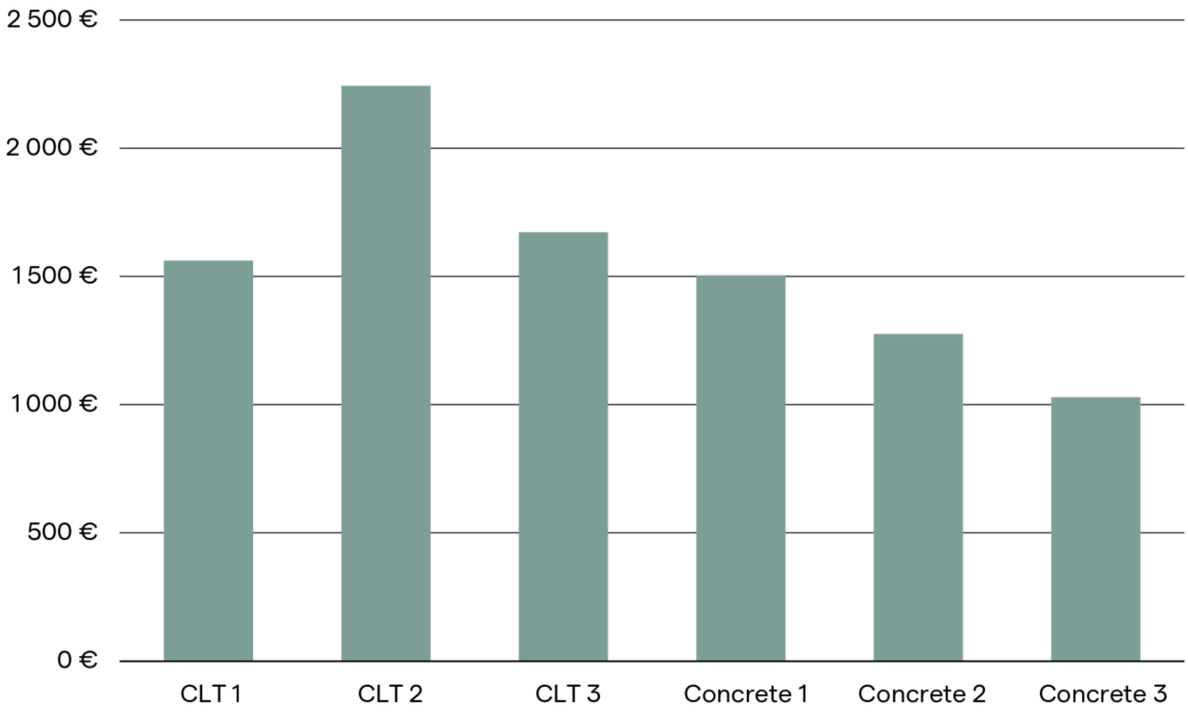

Figure 12 - Cost pr. GTA for the Norwegian cases, excluding fixed inventory and installations

The cost of six Norwegian cases presented in Figure 12 illustrates that the cost of the concrete buildings is still lower than the CLT building. However, the cost difference between all three CLT buildings and the concrete buildings have become lower but cost still varies within the CLT cases and the concrete cases. However, the largest variation was observed for CLT 2. According to the additional questions asked to the contractor of case CLT 2, it was commented that one of the reasons for the case CLT 2 to have a higher cost was that there is a large underground work for the basement constructed in concrete. For this basement, which includes parking areas, technical installation rooms and other functions beneath the whole building, it was required more blasting and other works which were costly. However, this shows that a higher cost of a CLT project do not necessarily need to be a result of the building being constructed in CLT but might be because of other conditions which affects the total cost more.

Furthermore, it is relevant to investigate the cost of the cases without *common cos*t, and *general cost*, and thereby only looking at the cost of the materials and labour cost during the construction. This investigation is shown in Figure 13 where the cost of *site preparation*, *ground conditions*, *load-bearing system*, *external walls*, *internal walls*, *slabs*, *roofs* and *stairs and balconies* is evaluated separately.

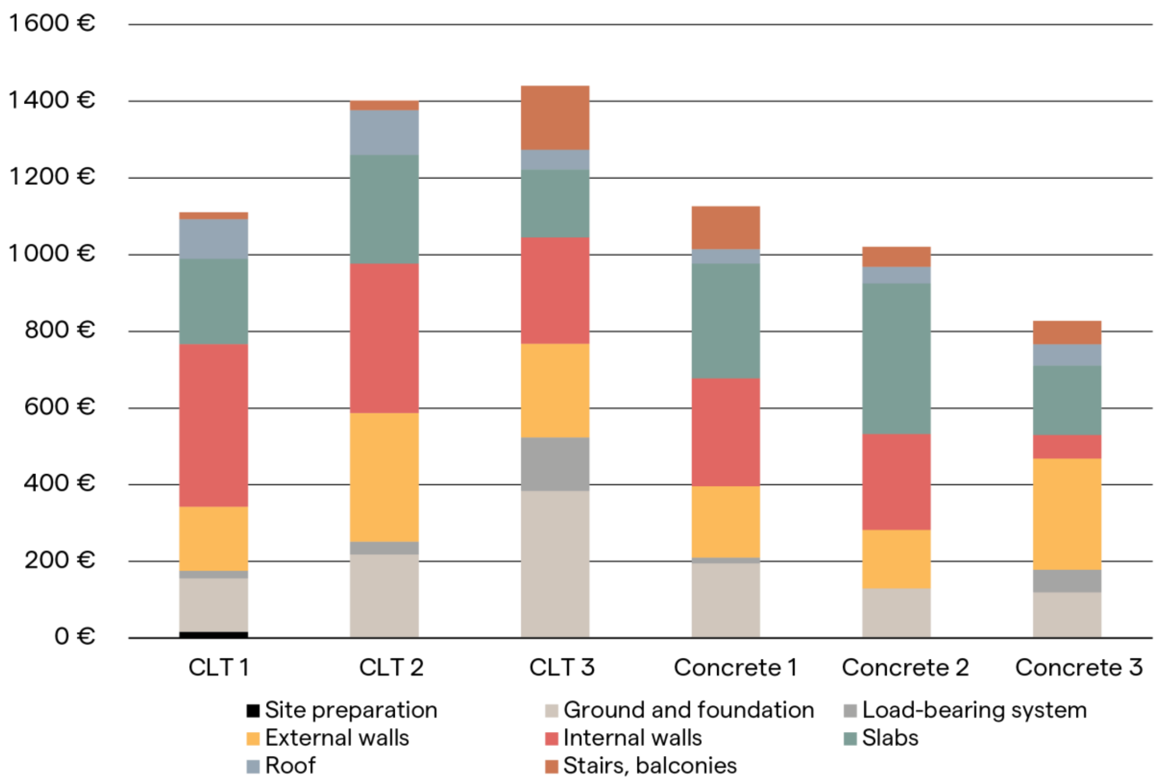

Figure 13 - Cost of the building parts including materials and labor cost

The results of the cost of the building parts show that the variation within the CLT buildings changed from case CLT 2 having the highest cost to case CLT 3 having a slightly higher cost per GTA. As mentioned earlier, the cost group *general cost* was not shown explicitly in CLT 3, thus this cost might be included in cost of the building parts shown in Figure 13. Therefore, it cannot be concluded that the building parts are the most expensive for case CLT 3 compared to the other cases.

Through the analysis of the Norwegian cases, it can be concluded that cost varies within the CLT projects and the concrete projects. But there is a tendency that the concrete building has a lower construction cost compared to CLT buildings.

4.2.2 Swedish projects

For the data collection of Swedish case buildings, there was a limited willingness to share cost data from the stakeholders' side. Also, for the ones who contributed with the data, the breakdown of the cost groups was not possible to provide with the level of details as the Norwegian cases. Thus, it was only possible to receive the total cost for three projects, two CLT projects and one concrete project. Table 9 and Figure 14 below shows the total cost per GTA for the three Swedish case buildings and the percentage difference from the highest cost per GTA of the three buildings.

Table 9 - Results of total cost per GTA for the Swedish projects

	CLT 4	CLT 5	Concrete 4
Total cost per GTA	1.970.48 €	1.915.45 €	2.231.65 €
Percentage difference from maximum	-11.7%	-14.2%	-

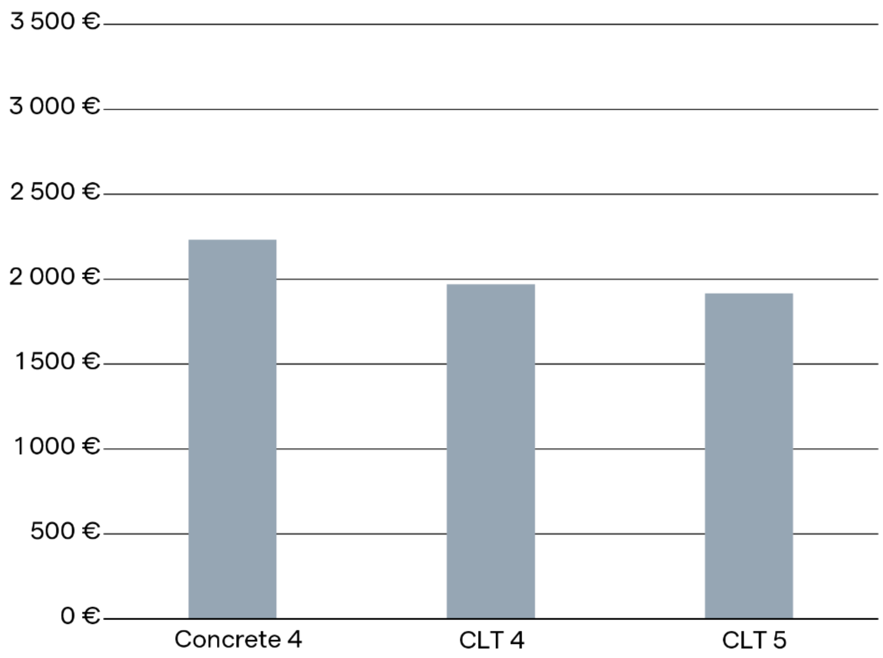

Figure 14 - Total cost pr. GTA for the Swedish projects

The results show that the two Swedish CLT case buildings has a respectively 11.7% and 14.2% lower cost than the concrete building. As mentioned above, the results of the Swedish projects are not divided into the same cost group structure as the Norwegian project and has only been given as a total of the construction cost. Therefore, it cannot be concluded which cost groups had the highest and lowest cost for each project. However, the contractor team of project Concrete 4 is different than the projects CLT 4 and CLT 5. Concrete 4 have had a combination of a turnkey contractor and an executive contractor, whereas CLT 4 and CLT 5 only have had a turnkey contractor. This might cause some cost differences. Furthermore, Concrete 4 consists of 14 building whereas CLT 4 consists of three buildings and CLT 5 only consists of one building. It can be assumed that the cost per GTA for the same total floor area becomes higher with increased length of building envelope (more windows, more insulations etc.). Thus, the cost per GTA for Concrete 4 might show somewhat higher number compared to a regular concrete building with just one volume.

Through the questions to the contractor for Concrete 4, Titania, they described that the cost of the final building ran over budget due to complication with the ground and foundations work. This as well might be one of the reasons for the higher cost for case building Concrete 4. Furthermore, Titania stated that if they had a more optimized logistic solution and a lower construction rate, they would probably have been able to save 5-10% of the total cost.

The case building CLT 5, which has the lowest cost per GTA of the Swedish project, can as well be defined as a hybrid building between concrete and CLT. The ground floor and the slab above the ground floor was constructed in concrete. The 1st and 2nd floor are mostly constructed with CLT. The contractor SJB bygg stated that the entire building would have been cheaper if the building was constructed in only concrete and steel or with a timber frame structure. This statement should however be seen in the context that SJB bygg are used to work with concrete and steel and timber frames, but not with CLT. Furthermore, they stated that if they are doing a similar project again the project time would be approx. 10-20% shorter, which should be reflected as a lower cost for the next time.

Moreover, the results illustrated in Figure 14 show that the CLT projects have a low variety for the Swedish project, whereas the earlier mentioned Norwegian projects has a larger cost variation between the CLT projects. Since we know the cost of only two Swedish CLT projects, it cannot be concluded that this shows a general tendency for Swedish projects, and this can be studied further in an additional study where more case studies are available. Even though the cost data of Swedish projects are limited in this study, the results of the Swedish projects still show that CLT buildings do not necessarily have a higher cost than concrete buildings. For a deeper analysis and investigation more project and cost data divided into a cost group structure are needed.

4.3 Analysis of interviews

The results of the interviews from the building industry and the case studies were analysed in order to recognize tendencies in the costs and methods to construct in CLT and concrete. Results are based on the described interviews in section 2.3 and are divided into different subject from the interviews.

4.3.1 Material cost

The contractors Veidekke and Adserballe & Knudsen, who both have constructed concrete building and CLT buildings, stated that it has been more expensive to build CLT buildings compared to concrete buildings up until June 2022 when the project has concluded. They both point out that the material cost has been higher on the CLT project they have been working on, compared to the material cost for a concrete project. The higher material cost has been a result of fewer suppliers and a long transportation. However, Adserballe & Knudsen stated that more suppliers are coming to the Nordic countries and therefore transportation prices have decreased in the last three years. Furthermore, Veidekke pointed out that due to the fire regulations in Norway large amounts of fire gypsum boards are needed and it increases the material cost of CLT buildings. In addition, a building of 8 storeys constructed in CLT in Norway would need a sprinkler system, which is not the case for a concrete and steel building in Norway. Thereby the material cost for a CLT building may increase further for a building of this height, by adding additional gypsum boards.

However, the weight of a timber building is lower than a concrete building, thus less material is needed for the foundation. This means that in areas with challenging ground conditions, the cost of the foundation can be reduced because of a lighter building.

The contractors and owners of the CLT cases stated that those case studies were planned as timber constructions from the beginning, and thus there was no solid cost comparison to other alternatives. Yet, as stated in section 4.4.2. according to the contractor, SBJ Bygg, CLT 5 projects would have become less costly if other conventional materials than CLT would have been used.

4.3.2 Time and logistics

Through the interviews with City of Växjö, Veidekke and Adserballe & Knudsen, they have all pointed out that construction time of CLT building have potential to be shorter than concrete buildings. Veidekke have had experience of shorten the construction time by two months by constructing a CLT building compared to a similar building constructed in cast-in concrete and steel. They had an assembly time of one week per floor in such a way as the following example:

On Mondays they started by marking all the placements of walls and stair elements and hereafter started assembling the walls. On Wednesdays they hoisted the bathroom cabins and all the materials needed for the interior finishes into the building. On Thursdays, they closed the storage and on Fridays they screwed the walls, decks and closed with acoustic measures. The following week they started over with the next floor.

However, it was pointed out that in order to shorten construction time, then the logistics is important to optimize. For Veidekke it was important that the CLT elements and materials arrived as planned every week, so that all the workers were able to do their job and follow the time schedule. But it was as well pointed out that the health and safety on site were beneficial for the workers of the CLT building.

On the first CLT project Adserballe & Knudsen did, they optimized the cost for deliverance of CLT elements by loading the trucks to the maximum, and thereby decrease the numbers deliveries. However, they found huge logistic challenges by handling all CLT elements before they needed them. It demanded to handle the elements 2, 3 and 4 times and every time with a risk for scratches and marks on the elements. Furthermore, the risk of moisture in the elements as a consequence of unstable Danish weather conditions and no weather protection on the site. From this experience they have learned to demand the CLT elements in the order they needed it for the assembly of the building, and thereby streamline the processes.

In addition, the interviews pointed out that CLT buildings constructed by an architect, engineer and contractor who have done a CLT project for the first time, have a higher project cost. City of Växjö stated that in the beginning the CLT projects in City of Växjö had a 20-30% higher project cost than concrete alternatives. As more CLT projects were built in Växjö municipality by various local contractors, the cost difference decreased to 10% between CLT and concrete, where CLT is still higher. During the pandemic period the construction cost was heavily influenced by it.

In addition Veidekke stated that the shorter construction time is beneficial for the developer of the project, since the occupancies can move into the apartments earlier and start paying rent, which means that the developer will save interest rate for the earlier incoming money.

In the case of City of Växjö, in 2013 they launched the policy that more than 50% of the newly built municipal buildings would be timber construction (including hybrid construction where timber is the primary material) by 2020. Their goal was not only reached but succeeded with an average of 70%. From the city planning viewpoint, the municipality appreciates buildings that are more prefabricated and faster to build as the disruption in the town is shorter. While there are several materials and ways to prefabricate, CLT shows a high advantage for high level of prefabrication.

4.3.3 Regulations and development of solutions for fire safety

Throughout an interview with Carl Pettersson from RED fire, it was described how the fire protection and fire regulations is an important part of the cost of a timber building.

Fire protection demands substantial efforts in all buildings, from planning and development to maintenance. However, the discussion and design of fire protection in CLT buildings have been all but a straight path to predictable and consistent solutions. What is seen when looking back in time is that the fire safety design solutions for CLT buildings vary greatly depending on who the fire safety consultant is. Since the solutions may contain extensive use of gypsum plasterboards, automatic sprinkler protection systems or fire-retardant treatment it is important to find safe and efficient solutions which also help keep the CO_2 emissions and costs as low as possible.

The greatest difference to consider, regarding CLT buildings compared to concrete buildings (with no or very little mass of combustible materials in the structure), is that CLT buildings contain much more combustible material in the structure. In case of a fire, when the combustible interior has burned out, the CLT building structure still needs to be protected or it will continue to burn.

In Sweden, the fire protection strategy for all buildings consists of two main parts. Provide sufficient time and safe evacuation of people inside a building and allow firefighters to conduct search and rescue operations. This differs from some other countries where the aspect of saving the property from damage in the event of a fire is also in focus. In these other countries regulations for CLT buildings are more detailed and conservative. In Canada and the USA, new regulations are in place to use a glue type which can withstand more heat named “PUR 2” glue instead of “PUR 1” which is commonly used in Sweden and Europe. In Sweden it appears that insurance companies are starting to require more fire protection measures compared to what can be found in the building regulations. At the same time, these requirements are also an acceptance that higher buildings built from wood are a part of the future in the building industry.

Some of the latest demands from an insurance company in Sweden are shown in Table 10.

Table 10 - Demands from insurance companies regarding fire protection of timber buildings

Apartment buildings	Demands from insurance companies
< 4 storeys	No demand for sprinkler system Normal regulations for the surfaces. Normal regulations for fire resistance.
4-8 storeys	Demand for residential sprinkler system connected to tap water. The apartments need no protection from flames on surfaces It could mean normal regulations for the surfaces. Normal regulations for fire resistance.
> 8 storeys	Demand for a conventional sprinkler system. It could mean normal regulations for the surfaces. Normal regulations for fire resistance.

With the special regulations for timber building required from the insurance companies and the national regulation it creates an additional cost of timber constructions compared with concrete and steel constructions. This as well were stated throughout the interview with Veidekke, where it was described that the additional material cost and labor cost for installation of fire gypsum boards constituted of a large part of the cost differences between their timber building and concrete building. Thus, it is important to consider the national fire regulations in terms of construction cost.

4.3.4 Weather protection

For the construction work of either a CLT building or a concrete building the weather is an important factor in the construction cost. Concrete must dry before the interior finish work can start, and if the humidity is high, it is more difficult to dry the concrete and might need heating equipment to dry the concrete. Timber constructions is built by an organic material and therefor is important to keep the material dry in order not to be infected by fungus or mold. Therefore, it has been investigated throughout the interviews and in the case studies what have been experienced in relation to weather protections. Through the questions for the case study buildings, it showed that none of the studied cases in Norway and Sweden used a tent to cover the construction for protection against rain. For the case CLT 3 VEF Entreprenør had to dry the construction with heated air, however they only did it for a very limited time. For case Concrete 3, VEF Entreprenør as well used heating to dry the concrete before closing the construction, but in a larger scale compared to case CLT 3.

During the project *Maskinparken 3*, whose cost data was not a part for this study, Veidekke did not use weather protection during the construction. They explained that due to the cold and dry weather in Trondheim they had no need for using a tent or drying, other than natural aeration. According to their experience, when they had snow, they could easily remove it and afterwards let the construction dry. Furthermore, they experienced that if they had snow or rain during a weekend, only a small amount of water had penetrated the construction. The construction was then easy to dry before closing it by gypsum boards and insulation. However, they stated that they had a great awareness of the risk of moisture during the entire construction period.

In addition to the risk of rain, they also had to be aware of the wind. When they had to hoist the large wall and deck elements it was important that the wind was weak. If it was too windy then they were not able to control the large elements with the crane.

In the case of Adserballe & Knudsen, they have bad experiences by constructing a CLT building in Denmark without using a tent or other weather protection. They stated that in Denmark they have other weather conditions than Norway, which might occur as a higher risk to build a CLT construction without a tent in Denmark than in Norway.

In the case of City of Växjö, two out of ten recent timber buildings were built under a tent, and others were exposed. Meanwhile, they stated that they have experience to save money by using a tent as a result of continuously dry work conditions, which does not incur waste of time by waiting for the construction to dry after accidental wetting.

5. Discussion

5 Discussion

5.1 Sensitivity and uncertainties

Throughout the process of data collection, it was clear that the project and results would be limited by the number of cases studies. Many of the companies who were contacted and asked to contribute to the project, did not had time or wanted to participate in the project. The limited number of cases resulted in a limited data base for the project, and therefore creates some uncertainties throughout the project. The uncertainties have been identified and are listed below.

Identified uncertainties:

- Representativeness of the collected data set
- Cost differences which are derived from different types of buildings (care homes, family apartments, apartment buildings with industry (dentist))
- Influence of the timing of the project in relation to the general economy and labor market
- Influence of different locations within each country
- Influence of different construction methods
- Influence of the variation of the contractor team
- Influence of the pandemic since 2020

The uncertainty of the representativeness of the data can cause a large sensitivity for the assessment since each project constitute to a large impact of average result. If just one project had a high cost per GTA as a result of e.g., bad ground conditions, it would easily affect the overall picture of the cost analysis as a whole in either CLT or concrete buildings. This means one particular situation of a project can lead to a different conclusion of the project. Nevertheless, the results of the cases examined in the project still show that a timber building does not necessarily need to be more expensive. In addition, the interviews and literature studies tell that there are other advantages and disadvantages in the construction methods for timber buildings, which cannot directly be seen in the total cost, such as the construction time and the health and security for the craftsmen in the factory and on site.

Another characteristic of a project which can result in a different cost per GTA is the type of apartment building. If the apartment building is a student housing or an elderly care home, the building consists of a lot of small apartments than another ordinary apartment building, and thus more fire compartments, internal walls, and more bathrooms etc. are needed. These extra materials might result in a higher construction cost pr. GTA compared to a family apartment building with larger rooms. Two out of the three CLT case buildings in Norway are care homes, but none of the concrete case buildings in Norway are care homes. Thus, there might be a chance that one of the reasons why most of the concrete case buildings in Norway have a lower cost compared to the CLT buildings. This is an uncertainty since it cannot be identified and compensated for through the material and data which have been available. However, the case buildings were limited to apartment buildings and therefore did not include building types such as offices, school, factories etc. which would have caused an even higher uncertainty.

Not all the case projects are built in the same year. Even though the costs have been index regulated for the price development of the construction industry, the numbers can still be affected by the time the building was built. For instance, there could be advancements in the construction techniques in 2021 compared to those in 2016. Moreover, the prices for different materials develop differently. One example from Denmark is that from June 2020 to March 2021 the material prices increased with 2% for cement, 12% for timber and 36% for iron and steel[20]. This means that even though the total cost is index regulated, the prices of each material are still sensitive towards its own price development. Thereby, the comparison of projects built during different time periods might cause an uncertainty for such an economic analysis. This must always be considered when project cost is compared.

In our study, the costs were only compared with other project within the same country. This was done in such a way since each country has its own market with different material prices different labor cost, different definitions of areas etc. However, there are also different prices within the countries. A project constructed in the northern part of Sweden most likely has a different price in the southern part of Sweden. This is as well an uncertainty in the project.

The global pandemic of corona virus caused a substantial impact on the global economy, and the construction sector have been also heavily affected in many regards such as labor cost, material cost, transportation cost, logistic, real estate price etc. Among the case buildings especially the ones which were built after the pandemic started, the contractors stated that there were only limited impacts of the pandemic on the construction cost. For example, the Norwegian CLT case building, CLT 2, which is still under construction as of June 2022, have been handled with fixed purchase contract. The Swedish CLT case building, CLT 5, did not have an issue with the labor force as the contractor has been working primarily with local workers from the region. As the

[20] Danmarks statistik, *Priserne på byggematerialer stiger fortsat voldsomt*, https://www.building-supply.dk/article/view/786858/priserne_pa_byggematerialer_stiger_fortsat_voldsomt, 15.04.2021

sample size is limited, it is not possible to draw a conclusion of the tendency. But the influence of the pandemic on the construction cost might become more apparent in the near future.

5.2 Legislative framework and market trend

European and national regulations and taxation may have a significant impact on the selection of construction methods and materials. This section reviews and discusses the legislative framework on GHG emissions and taxation in the Scandinavian countries.

In January 2022, the national building regulation in Sweden was revised, and a new requirement states that new buildings needing a building permit must submit a climate declaration before the building can get clearance to be used[21]. The declaration is based on the GHG emission calculation through the Life Cycle Assessment (LCA) method, and it is mandatory to include the production stage and the construction stage of the construction project (A1-A5). The parts of the building that must be included are thermal envelope, load bearing structure and non-load bearing inner walls.[22] As of today (June 2022), there is no limitation on the GHG emission per floor area. However, the first step of the GHG emission limitation is planned to be implemented in 2027. There is not yet information on what the limits will be, but Boverket (the Swedish National Board of Housing - Building and Planning) has recommended that early stage LCA should be made in order to meet the criteria of the future limits[23].

In Denmark the national building regulations will from the 1st of January 2023 include a GHG limitation for buildings of 1000 m^2 and above[24]. In Denmark the LCA calculations will include the production stage (A1-A3), replacements of building parts (B4), energy use during the use stage (B6) and end-of-life stage (C3/C4). The LCA calculations is required to have a calculation period of 50 years, and will include the building basis, primary building parts, architectural finishes, surfaces,

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[21] Boverket, *Ny lag om klimadeklaration of uppdaterad klimadatabas*, https://www.boverket.se/sv/klimatdeklaration/om-klimatdeklaration/nyheter/ny-lag-om-klimatdeklaration-och-uppdaterad-klimatdatabas/

[22] Boverket, *Klimadeklarationens omfatning*, https://www.boverket.se/sv/klimatdeklaration/gor-sa-har/omfattning/, 30.09.2021

[23] Riksdagen, *Lag (2021:787) om klimadeklaration för byggnarder*, https://www.riksdagen.se/sv/dokument-lagar/dokument/svensk-forfattningssamling/lag-2021787-om-klimatdeklaration-for-byggnader_sfs-2021-787, 01.07.2021

[24] Indrigs og boligministeriet, *Aftale mellem regeringen og Venstre, Dansk folkeparti, Socialistisk folkeparti, Redikale venstre, Enhedslisten, Det konservative folkeparti, og Alternativet: om National strategi for bæredygtigt byggeri.* https://im.dk/Media/C/4/Endelig%20aftaletekst%20-%20B%c3%a6redygtigt%20byggeri%20-%205.%20marts%202021.pdf, 05.03.2021

and installations. The 1st of January 2023 the GHG limits will be of 12 kg CO_2 eq/m^2/year, but will be tightened in 2025, 2027 and 2029[25].

1st of July 2022 the Norwegian building regulations will include calculations of GHG emissions for apartment buildings and commercial buildings. The calculations are required for new built or extensive transformations and must be based on the Norwegian standard NS 3720:2018. As a minimum the calculations must include the stages A1-A4 (production stage and transportation to construction site), B2 (Maintenance), B4 (operational energy) and waste on the construction site. The GHG emissions must be calculated for; pile foundation, direct foundation, load bearing system, exterior walls, interior walls, slabs, and roof. As for the calculations of GHG in Sweden, there is no limitations for the level GHG in Norway[26].

The focus of limiting the CO_2 footprint of buildings in the Nordic countries will create an incitement to use material with embodied CO_2 emissions. Timber can be a great alternative to concrete and steel in terms of reducing the CO_2 footprint of the building, thereby the focus of timber buildings might increase. If this leads to a higher demand of timber buildings, it might decrease the price of materials as long as there are no resource shortage situations and more people will be skilled in this type of design and construction work for timber building. Thereby the total price of timber buildings might decrease.

However, timber is not the only way to decrease the CO_2 emissions for buildings. Other technical solutions exist such as more compact building design, building structure optimization, usage and developing concrete/steel with lower CO_2 footprint, energy efficiency of buildings, recycle and reuse of materials, etc. Furthermore, focus might change to investigate the possibilities of renovating buildings instead of constructing new buildings or to build smaller buildings instead for large building volumes. All these alternatives have different costs, and it will change the building industry and the market from what it is today.

In parallel to the focus on the CO_2 footprint reduction of buildings, there is a focus on the CO_2 emissions reduction for all industries in the Nordic countries as well. In Denmark it has been decided to introduce CO_2 taxes on industries who emits large amounts of CO_2 emissions. This means that industries will be evaluated on the amounts of CO_2 emission they emit and thereby have to pay a certain amount of tax related to the emissions. This implies that e.g. the concrete

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[25] Høringsportalen, https://hoeringsportalen.dk/Hearing/Details/66338, 22.04.2022
[26] Regjeringen.no, *Forskrift om endring i byggeteknisk forskrift*, https://www.regjeringen.no/contentassets/a4d0d514468549b690cc7b72a9985b8e/forskrift-om-endring-i-byggteknisk-forskrift.pdf, 01.06.2022

factories, who are known to have a high CO_2 footprint from their production, will be demanded to pay additional taxes for their production. This might either increase the cost of concrete or promote the innovation of new concrete with lower embodied carbon.

Furthermore, the EU initiative, the EU taxonomy, is a part of the environment agenda. The EU taxonomy is an EU-wide emission trading system, which will put a price on emissions from the building sectors and is planned to start from 2022[27] [28]. It is expected that this will incentivize developers and investors to choose the invest in buildings with a lower carbon footprint.

The change in the demand for material's carbon footprint may result in the different demand for the raw materials as well. If the demand for the timber would increase rapidly while the production capacity for sawn timber would not follow as quickly, there might be a potential for the raw material shortage. In fact, a sharp increase of sawn timber price was observed globally during the recent pandemic as the demand for sawn timber increased very suddenly.

All these changes will put pressure on the innovation and development of the building industry and as seen in the case studies and interviews, it might cause additional cost when new methods must be developed. This means that the market of the building industry is about to change, due to the focus of reducing the CO_2 footprint of buildings. And this will affect both the concrete industry and the timber industry.

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[27] European commission, *EU taxonomy for sustainable activities*, https://ec.europa.eu/info/business-economy-euro/banking-and-finance/sustainable-finance/eu-taxonomy-sustainable-activities_en, 23.06.2022
[28] EU technical expert group on sustainable finance, *Taxonomy: Final report of the technical expert group on sustainable finance*, March 2020

6. Conclusion

6 Conclusion

The results found throughout the analysis reflect the cost of cases of CLT buildings and concrete/steel buildings in Sweden and Norway, as well as information from interviews of stakeholders. The results showed tendencies of how the cost have been at the time where the buildings were designed and build. As described in the discussion, the market develops continuously, especially within more projects with a stronger focus on sustainability. Therefore, it is important not to apply the conclusions of the case studies as an exact forecast for future buildings but must be used as an indicator of the costs and what to be aware of due to cost of timber and concrete buildings in the Nordic countries.

The following are the main findings of the study of constructions cost of CLT buildings compared with concrete/steel buildings:

- There is a tendency that the CLT buildings has a higher construction cost compared with the concrete buildings for the Norwegian case buildings.
- The cost of a CLT building does not necessarily need to become higher compared to a concrete building. It depends on the type of project and how it is executed.
- The more experience one has with CLT buildings, from cost calculation to designing and constructing, the more likely the building becomes more cost efficient.
- The material cost is often higher for CLT buildings compared with concrete buildings.
- The prefabrication of CLT modules most often result in a shorter construction time as well as better working conditions in the factory and on site.
- The logistics of a CLT building is different than for a concrete building and most be considered carefully to lower the cost.
- CLT buildings are lighter than concrete ones and in many cases that presents an advantage on foundation costs.
- In order to optimize timber construction in both structural system with realistic dimensioning and material cost, it is important to engage an engineer in the early phase of the project planning.
- None of the cases studies used a tent as weather protection, but it is stated that it possible to save money when applying a tent, due to a more continuously workflow.

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8. Appendix

Appendix

Appendix 1 – Original data for the case buildings

Appendix 2 – Data for index regulation and currency conversion

Appendix 3 – Interviews

Appendix 3.1 – Olivia Thim, Växjö Municipality

Appendix 3.2 – Erlend Dragesæt, Veidekke

Appendix 3.3 – Jakob Kock, Adserballe & Knudsen

Appendix 3.4 – Carina Herbertsson and Maria Dahl, Växjöbostäder

Appendix 3.5 – Jens Hagelberg, SJB bygg

Appendix 3.6 – Petter Pallesen, VEF

Appendix 3.7 – Richard Hansen, Solid

Appendix 3.8 – Wojciech Wondell, Titania