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Circular economy in the built environment – A state-of-the-art study on methods for the reuse of building components

Sirkulær økonomi i byggenæringen – En toppmoderne studie på metoder for gjenbruk av bygningselementer

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I Acknowledgements

The master thesis is written during spring of 2022 on the behalf of Building Technique and Architecture, the REALTEK Faculty at the Norwegian University of Life Sciences (NMBU). The work is performed individually and is weighted with 30 credits.

This thesis symbolizes the acquiring of a master's degree in engineering and the end of a five-year study at the university, but it also represents the bridge from education to the beginning of a professional working career. During the fall of 2021 an idea started circulating around the topic of sustainability and reuse in the building industry. Early January 2022 a systematic and dedicated process of literature review and reading begun. Since then, the thesis has provided long days and frustration, but most of all knowledge and enlightenment. Seeing how fast the construction practice is developing and how current this topic is today has been incredibly inspiring.

There are a lot of people that deserves recognition for their support. First, I would like to express my sincerest gratitude to my supervisor at NMBU, Associate Professor Themistoklis Tsalkatidis. Through the entire semester he has provided support, knowledge, and inspiration through weekly meetings. Our conversations have undoubtfully been a source of motivation, for this I am thankful.

Experts from the industry should be acknowledged for have taken the time to talk with me and invited me to sit in on meetings and workshops, allowing me to soak up their knowledge. I would like to thank my family and friends for always contributing with their unconditional kindness and support. Finally, a thank you to all my fellow students at NMBU that have made my five years as a student a time of joy and a period I will look back at with pride and happiness.

"Buildings should coexist as a dynamic system, not function alone as a static object" (Nilsen, Søren).

Ås, 10th of May 2022

Jon Øvereng Aunet

II Abstract

Our planet is currently facing the biggest challenge in the history of mankind. Rapid and brutal environmental changes are threatening existence as we know it and the only solution to this problem is to turn our utmost attention to sustainability. The building and infrastructure sector should in no way be given a free pass in this turn-around, on the contrary it should lead the way. The industry is responsible for an enormous consumption of energy and raw materials, draining limiting resources.

Circular economy has across sciences been accepted as strategy with the potential to motivate a shift from a linear to a circular consumption of resources. A fundamental idea of circular economy is to close the material loop. In other words, produce less, minimize waste, and instead reuse. In the building sector reuse and recycling are considered important to secure a sustainable industry. Unlike recycling, reuse demand few resources to fill a new purpose, making it a valuable practice with a low carbon footprint. Therefore, the industry is looking at different ways to implement reuse as a part of modern structural design.

The structural system of a building represents a large share of the total mass, so this results in that the reuse of structural components should be a priority. Harvesting elements from existing buildings and demolition projects can remove the need for virgin production and by this reduce the environmental impact of a new project. Current work and research are trying to bridge the gap separating the potential and the practice of reuse. The first products of this work are recently published as the BREEAM-NOR v.6.0. Manual and Standard NS 3682:2022. These have already showed great value and importance.

Research reviewed in this study have revealed that limited documentation and uncertainties regarding materials and their properties are limiting the practice of reuse. To increase the value and efficiency of reuse in the future, the industry has started to consider the reuse potential already during the design phase. An important contribution is the implementation of design for deconstruction (DfD) and material passports (MP). Methods that provide more information and increases the transparency, yielding dynamic structures adaptable to future changes.

III Sammendrag

Kloden opplever for øyeblikket den største utfordringen i menneskenes historie hittil. Raske og brutale miljøendringer truer eksistensen som vi kjenner den og den eneste redningen er å rette vår fulle oppmerksomhet til bærekraftige løsninger. Bygg og infrastruktur-sektoren burde på ingen måte få slippe unna omveltningen, men burde heller gå foran som gode forbilder. Byggenæringen står ansvarlig for et enormt forbruk av energi og råvarer, dette tapper jorda for begrensede ressurser.

Sirkulærøkonomi har på tvers av flere vitenskaper blitt akseptert som en strategi med potensialet til å motivere et skifte fra et lineært til er sirkulært forbruk av ressurser. En fundamental tanke med sirkulærøkonomi er å lukke kretsløpet til materialene. Med andre ord, produsere mindre, minimere avfall og heller gjenbruke. I bygg- og anleggsektoren er gjenbruk og resirkulering vurdert til å være viktig for å sikre en bærekraftig byggenæring. I motsetning til resirkulering, så krever gjenbruk lite til ingen prosessering til å fylle et nytt formål. Det gjør gjenbruk til en verdifull metode med lavt karbonavtrykk. Bransjen undersøker derfor ulike metoder for å implementere gjenbruk som en del av moderne konstruksjonsteknikk.

Bæresystemet til et bygg representerer en stor del av den totale bygningsmassen. Dette tilsier at gjenbruk av strukturelle komponenter burde være en prioritet. Ved å innhente elementer fra eksisterende bygninger og rivingsprosjekter kan behovet for ny produksjon bli mindre og dermed redusere klimafotavtrykket til nye prosjekter. Moderne forskning forsøker nå å finne løsninger som kan knytte sammen potensialet og utførelsen av gjenbruk. De første produktene av dette arbeidet er to dokumenter som nylig ble publisert som henholdsvis BREEAM-NOR v.6.0 og Standard NS 3682:2022. Disse har allerede vist bemerkelsesverdig viktighet og potensiale.

Forskning studert i denne oppgaven har avdekket at begrenset dokumentasjon og usikkerhet knyttet til materialer og deres egenskaper begrenser praktiseringen av gjenbruk. For å øke verdien og effektiviteten av gjenbruk i fremtiden har byggenæringen nå begynt å vurdere gjenbrukspotensialet allerede i designfasen. Et viktig bidrag til dette er design for demontering (DfD) og digitale pass for materialer (material passports, MP). Metodene gir mer informasjon og øker transparentheten. Dette resulterer i dynamiske bygninger som er tilpasningsdyktige og rustet for fremtidige forandringer dersom de skulle oppstå.

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Notation

CE	Circular economy
GHG	Greenhouse gas
EU	European Union
EEA	European economic area
TEK17	Regulations on technical requirements for construction works
DOK	Regulations for documentation of building materials
LCA	Life cycle analysis
LCC	Life cycle costs
EPD	Environmental product declaration
BIM	Building information model
3 R´s	Reduce, reuse, recycle
DfD	Design for deconstruction
CDW	Construction and demolition waste
ULS	Ultimate limit state
SLS	Serviceability limit state
CE certification	Manufacturer or importer affirms conformity with European health, safety, and environmental protection standards.
GL	Glulam
CLT	Cross laminated timber
LVL	laminated veneer lumber
MP	Material passport
BAMB	Building as material banks
GPR	Ground penetrating radar
MILP	Mixed integer linear problem
ECC	Embodied carbon coefficients
PVC	Polyvinyl chloride, plastic material
DiBK	Directory of building quality

Notation in the numerical example

$M_{in}(M_{R,in})$	Amount of input material to the product system that has been recovered (recycled or reused) from a previous system (determined at the system boundary)
$M_{out}(M_{R,out})$	Amount of material exiting the system that will be recovered (recycled or reused) in a subsequent system
Q_{MR}	Quality of the secondary material
Q_{VM}	Quality of the virgin material
Y	Recovery process yield or efficiency. Represent the ratio of waste input mass and new product mass (for instance the ratio of steel output to scrap input).
χ	Lifecycle impact (burden or credit) of product recycling or reuse beyond the system boundary
χ_{MR}	Lifecycle impact (burden or credit) arising from the material recovery
χ_{VM}	Lifecycle impact (burden or credit) arising from the acquisition and pre-processing of virgin material
E_{VM}	Environmental impact of the virgin material
E_{RM}	Environmental impact of the recovered material

1. Introduction

Our planet is without a doubt experiencing climate change. The past decades there have repeatably been registered new maximum temperatures during summers, the rate of forest fires have gone up, and the glaciers are melting on all continents. It is no reason to wonder if humans are to blame for these climate changes. A vast quantity of research and scientific results shows that a major reason for the global warming is the emission of greenhouse gases (GHG). During the last decades we have released enormous amounts of GHG through the combustion of fossil fuels such as coal, oil, and gas (Røyne, 2020).

According to the United Nations International Resource Panel (IRP), the world population will within 2050 need almost 3 planet earths to cover the global consumption if nothing is done to deal with the current squandering. The global use of materials such as biomass, fossil fuels, metals and minerals are expected to double the next 40 years and the annual generation of waste could increase with up to 70% before we reach the year 2050 (Norwgian Government, 2021).

The Paris Agreement was passed in 2015 and the goal is to that avoid global warming exceed 2°C and preferably stay under 1,5°C. Norway was one of the first countries to commit and has made promises to reduce the release of GHG by 55% within 2030 (Norwgian Government, 2021). Even though these are ambitious goals, studies show that it is not enough done to reduce emissions. Average global temperatures have increased with 1,05°C since the beginning of the 1900s and with the current outflow of GHG there will be a 0,2°C increase every decade. The emissions in Norway from 1990 up until 2009 experienced a reduction of only 2,3%. If this rate of reduction were to continue the global warming could reach 3°C within the year 2100. A change so critical it can lead to environmental changes out of control and irreversible consequences (United Nations Association of Norway, 2021).

Globally the building and construction industry alone accounts for almost 40% of the energy consumption and nearly 25% of the direct carbon emissions (International Energy Agency, 2019). To reach the overall goal of 55% reduction within 2030, the building sector needs to reduce their emissions with 60%. This equals an annual reduction of 7,6%, over three times more than the overall reduction in Norway between 1990-2009 (Wiik, 2020). Research shows that a large portion of the total emissions are connected to the building mass and mass-related processes such as production, transport, and end-of-life treatment (De Wolf, 2019).

Out of all buildings estimated to exist in 2050 it is assumed that 85-95% of these have already been built (European Comission, 2021). Researchers, the building industry, and officials all agree that this building mass is a resource that should be utilized and not disposed of. The importance of exploiting already existing resources is significant from a sustainability perspective and fundamental regarding circularity.

Instead of new buildings and production based on raw natural resources, the construction industry has experienced an increased focus on adaptivity and reuse. Reuse of components can help the building sector shift over from a linear to a circular economy, closing the material loop.

1.1. Thesis outline

The scope of this thesis will be to evaluate the current practice and potential benefits of reuse in the Norwegian building industry. To concretize the topic, the following research questions will be considered:

- Is reuse considered as a valuable and sustainable action in the building industry?
- What are the motivations and potential benefits of reuse?
- What is the status quo on reuse in Norway and what is potentially keeping reuse from being more common in structural design?

1.2. Objective

The objective of this thesis is to shed light on the current practice and potential benefits of the reuse of building components in the Norwegian construction and infrastructure industry. This is a topic that is considered important but has proven to be challenging due to a void in the standardization and verification of used building elements. This thesis tries to detect and present methods of reuse and simultaneously explain how these can lower the environmental impact of the building industry. The dissertation also takes aim to identify how important aspects such as technology, material type, geography, and economics influence the practice of reuse. Finally, the objective of this thesis is also to evaluate the cutting-edge research and technology related to the topic to predicate the potential of reuse in the years to come.

1.3. Background/motivation

Sustainable building design has until recently focused mostly on material efficiency, sustainable energy systems and material considerations for optimizing the structure in regard of low mass and energy efficiency. Along with the introduction of circular economy the principle of "closing the material loop" became an important term. Recycling was for a long time a priority in the loop-closing processes. Nowadays, the scientific community and building industry realizes that materials should be kept at their highest value of utilization for as long as possible. This is why reuse inhabits such great potential in the transition to a circular economy.

1.4. Limitations

This thesis aims to discuss and elaborate the newest and most impactful research related to circular economy and reuse in the building industry. The objective is to be unbiased and to create a diverse and nuanced evaluation of the current state of reuse. Some limitations have been made to create a defined framework allowing the research to be verifiable.

To ensure that the information and findings used in this thesis is up to date and reliable, all articles and research papers used as valuable sources of information have been published in the last 5-6 years. Practical case studies and documentation reviews have been restricted to be Norwegian, this is to evaluate the current state of reuse for this nation particularly. Therefore, creating a framework solid enough to argument around the current state of reuse in Norway has been important.

Though there is a vast number of building materials available in the market, only steel, concrete and timber are considered in this thesis. This is because these three materials that are the most common in structural design and by this the most influential in the consideration of large building components for reuse.

This thesis presents a numerical example based on the production, reuse, and recycling of steel. Because of material dependencies some the formulations are only fully applicable for steel scenarios. To sum up, most of the theoretical foundation and formulations are transferrable to timber and concrete cases.

2. Methodology

This chapter presents scientific theory about methodology and elaborates around the methodological choices taken for this paper. Scientific research is a way of presenting clear answers on problems. Research has several areas of use, such as finding rules, testing and discussions of findings or collecting objective data. There are two main methods of scientific research, one being qualitative and the other one is quantitative (NDLA, 2019). Qualitative methodology is the one used in this thesis.

Qualitative methods aim to capture opinions and experiences that are difficult to measure or quantify. The method is especially appliable if there is a gap of knowledge regarding the topic that is being studied (Dalland, 2017). An advantage of a qualitative methodology is that there are little restrictions on the type of data that can be collected and used in the research. A disadvantage with qualitative methods is that they are resource demanding and often result in an abundancy of information. The data can be nuanced and complex, making it difficult to filter the information most important to the research. Qualitative data will in many cases be based on a limited number of sources, making it hard to create a representative foundation and equally difficult to make general and unbiased conclusions (National Committee for Research Ethics, 2019).

Validation of results can be challenging. One way evaluating the results is through something called methodology triangulation. This is a method based on using several methodical techniques to respond to a scientific problem. If one obtains the same results with different methods this strengthens the reliability of the results. Triangulation also reduces the risk of biased considerations (Jacobsen, 2005).

Reviewing both existing data in literature and new data from the field, this thesis uses different types of methodology. By doing this data can be collected from a variety of sources, creating an objective and unbiased foundation. The theory of triangulation will be used to see if there is correspondence between research, theoretical practice, and on-site execution.

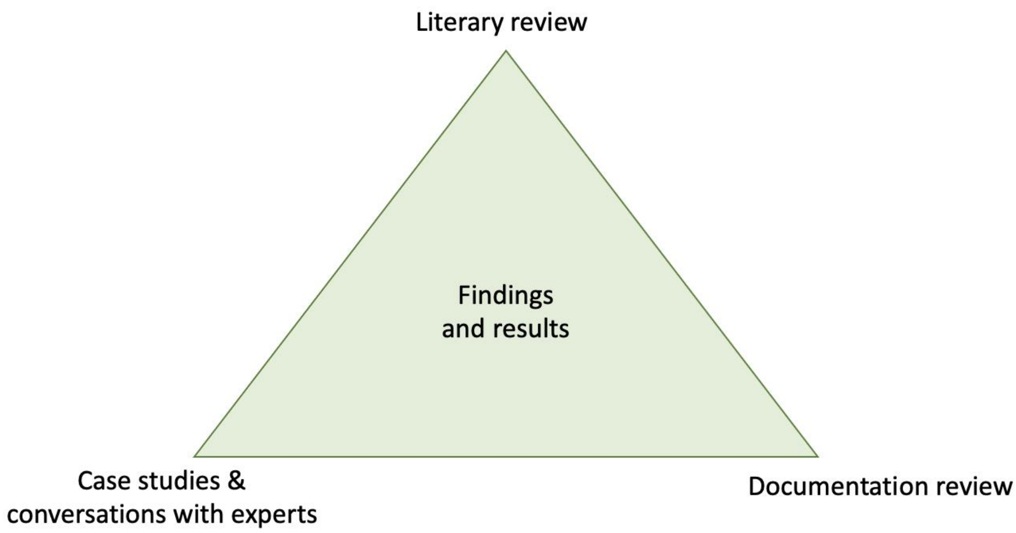

Figure 1 - Methodology triangulation illustration

The work with this master thesis is divided in three, consisting of a literary review, documentation review, and conversations with experts from the industry along with case studies (figure 1). The approach of each method will be presented in the next sections.

2.1. Literary review

Literary review is a well-established qualitative methodology. It is a method suited to provide an overview of current research within a scientific topic or to reveal gaps and needs for further research. In this thesis there has been used several search engines to gather relevant scientific publications. In the engines it has been possible to include Boolean operators to modify the searches. Such an example is the operator "AND" that has been used to include more phrases and by this limiting the number of publications in the search results. Another example is that the operator "…" has been used to decide that the document must contain a specific phrase.

2.1.1. Search engines

Oria

Oria gives access to all the academic publications from the NMBU University library, along with other institutions such as NTNU (Norwegian University of Science and Technology). The search engine allows to apply filters to limit the search results, e.g., language, date published and faculty.

Science Direct

Science Direct contain large quantities of full text scientific publications from all over the world and allows to evaluate the statistics of a publications, writer(s) etc. based on the number of citations. In addition to this there are many filters in the search engine that can be applied to limit the search results.

Google Scholar

The search engine of Google contains articles, books, and other types of scientific publications. It is a useful tool because it provides a high number of results and automatically present them based on integrated credibility criteriums such as publisher, citations, and writer(s). A potential fall pit of using google scholar is that it doesn't separate between articles which is peer reviewed and not.

2.1.2. Search words

Table 1 presents an overview of the search words and phrases used in the literary search. Circular economy is a term widely used across many sciences and practices resulting in many different search words and phrases. To obtain the biggest reach possible the searches have been performed in English.

Table 1 - Overview of the search words and phrases used in the literary searches

Search word/phrase	"AND"	"OR"
"Circular economy"	Buildings	
"Circular economy"	"Building engineering"	
"Circular economy"	"Structural design"	
Reuse	Engineering	
Reuse	Engineering “AND” Building	
Reuse	Components	Elements
Reuse	BIM	LCA
"Design for deconstruction"		
"Design for deconstruction"	BIM	
DfD		
DfD	reuse	
BAMB		
BAMB	MP	
BAMB	DfD	Reuse
"Material passport"		
"Material passport"	Reuse	BIM
"Buildings as material banks"		

The literary review has developed during the work of this thesis. Studying current research and conversations with experts from the industry have shed light on topics and problems that previously had been unthought of by the author. The search for relevant literature in this thesis has therefore been an iterative process.

2.1.3. Snowballing

Some of the literature obtained for this thesis has been obtained by snowballing, both "backward snowballing" and "forward snowballing". Backward snowballing is when one goes through the references of already obtained literature and discovers new and relevant articles. Forward snowballing is finding new literature by looking at publications that has cited the works that one has just read (Wohlin, 2014).

2.1.4. Validations, reliability, and limitations

During the work for this thesis there has been made continuous considerations regarding the reliability of the information creating the framework of this thesis. One being that all scientific publications such as articles and reports used should have been published within the last 5-6 years. This limitation is set because circular economy in the building industry is a new and fast developing topic, making only the newest research relevant. New and relevant data is important for the credibility for this paper, this secures that the findings presented are based on modern research and updated information.

To secure valid and reliable information scientific, all articles and reports cited in this thesis have all been peer reviewed and most of them have been published in acknowledged journals. This have been considered a sign of credibility by the author. Of such journals the following can be mentioned as examples: *Construction and Building Materials, Cleaner Production, Building Engineering* and *Waste Management and Production*.

2.2. Documentation review

Two different, newly published documents are evaluated in the thesis. One being the new BREEAM manual, BREEAM NOR 2016 v.6.0. and the other is the standard NS 3682:2022 that is for testing and verifying hollow core slabs for reuse. Since these were both published during the work of this thesis, there is a limited amount of literature commenting the documents. During the work for this study the documents have been thoroughly evaluated and considered against the topic for this thesis.

2.3. Case studies and interviews with experts

For this study two different case studies relevant for the topic have been reviewed. They are both in Norway, but in different parts of the country. Reason for using case studies is to shed light on the practical aspect of the topic presented. Often there are challenges when theoretical ideas are to be practically executed, therefore modern and practical examples are essential to create a full picture of the current state of the presented subject.

To connect this thesis with the building industry in Norway it has been performed interviews and conversations with experts from the industry. The findings from these talks will be considered against the findings from literary- and documentation reviews. The interviews and conversations are not directly cited since they are not to be used for anything else than reflection around the topic.

3. Theory

3.1. Circular economy

Historically the concept of circular economy (CE) is a relatively new term. The idea of a circular economy was first proposed by Chinese scholars in 1998. Four years later in 2002, circular economy was formally accepted by the Chinese government as a development strategy to counteract on the consequence from rapid economic growth and shortage of raw materials and energy (Yuan, 2008). The source of inspiration for this philosophy was again based on industrial ecology concepts in Germany and Sweden, where the focus was on loop-closing processes. In practice this meant moving away from the traditional linear production line that was based on "take-make-dispose" principles and rather adapt to a circular approach (figure 2) (Norouzi, 2021).

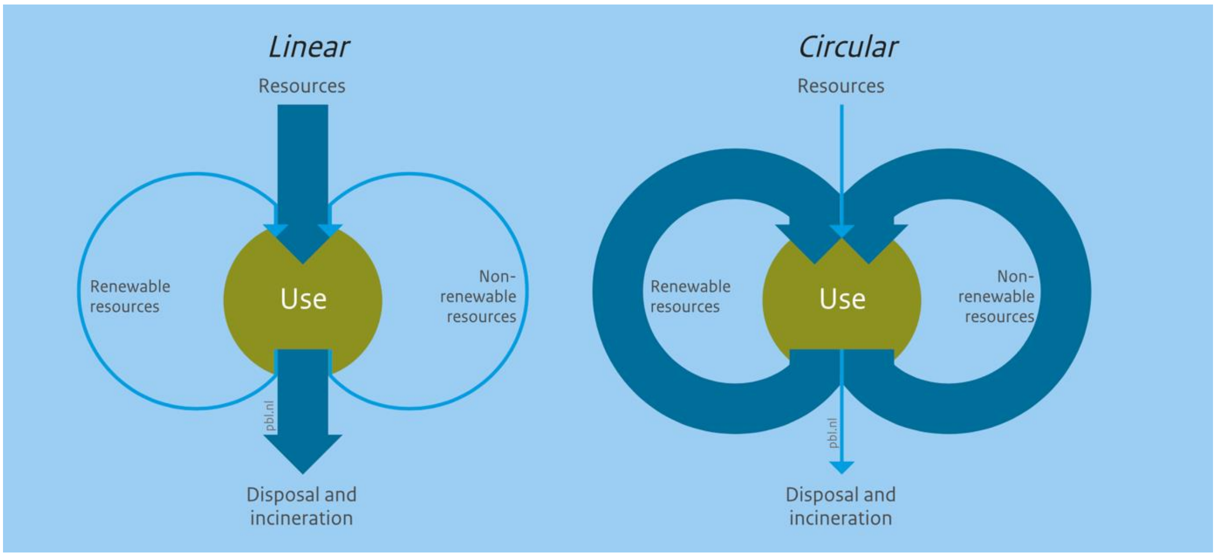

Figure 2 - An illustration of linear and circular strategies (PBL The Netherland Environmental Assessment Agency, 2017)

Circular economy has evolved from various scientific areas of research with a shared direction for future development, e.g., industrial ecosystems and industrial symbioses, the 3R´s principle (reduce, reuse, and recycle), cleaner production including manufacturing systems, circular material flows, natural capitalism, the concept of zero emissions and others (Ellen Macarthur Foundation, 2020). In the scientific community, there is no consensus for *one* common definition to the term circular economy. But despite the lack of a general acknowledgement for a single definition, there is agreement among scholars and researchers that CE is about prolonging the lifespan of components, materials and products through reuse, repair, recycle, remanufacturing and refurbishing. By following these principles one can avoid premature disposal and end of life (Zacho, 2018). Based on a literary study on circular economy in the building industry done by Benachio et. al. (2020) it was clear that many of the most frequently used definitions for CE circulated around these mentioned topics. According to the literary review the most cited definition is the one proposed by the Ellen Macarthur Foundation:

"*Circular economy is restorative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles*" (MacArthur, 2020). This is the definition that will be used in discussions related to CE principles later in this thesis.

3.1.1. Circular economy in the building industry

The fundamental philosophy of circular economy does not change moving from one industry to another. However, there are different focus areas depending on the science and industry that we examine. In the early stages of CE in the building industry the focus was on energy reuse and reduction of the *operational carbon*. Operational carbon relates to GHG (greenhouse gas) emissions during the use-phase of a building, which includes heating, cooling, ventilation, lighting, and equipment (De Wolf, 2019). Great progress has been made in developing energy-effective buildings and energy systems, in addition to prioritizing clean energy resources to operate the buildings. An official report published by the International Energy Agency in 2019 shows that the building and construction industry alone accounts for almost 40% of the global energy consumption and nearly 25% of the direct carbon emissions (figure 3) (International Energy Agency, 2019). The report further presents how the expected population and economic growth will increase the demand for steel (30%), cement (10%) and aluminum (75%) through to 2060 relative to 2017 levels. Note that this does not consider changes in the way materials are consumed by the construction industry.

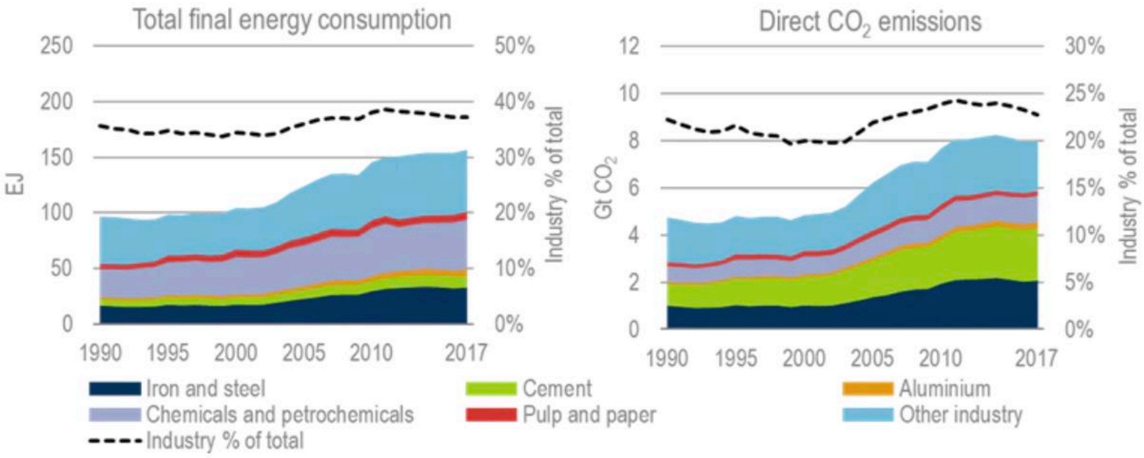

Figure 3 - Total final energy consumption and Direct CO2 emissions.

Industry % of total is industry divided by industry plus non-industrial sectors. Direct CO2 emissions do not include indirect emissions from producing the electricity consumed (International Energy Agency, 2019).

Based on data from the European Union it is expected that by the year 2050, 70% of the population in western countries will live in big cities, increasing the already existing pressure on infrastructure and residence capacity (European Union, 2019). The increased demand for virgin materials and related production of waste, population growth and urbanization will create challenges for sustainability. An example of such a case is how the growing material demand up until 2060 can lead to an approximated increase of 15% in CO2 emissions compared to 2017 levels (International Energy Agency, 2019). According to the Global Footprint Network the human population is consuming the planet´s natural resources 1.7 times faster than the planet can regenerate. This means that if nothing changes, it will have devastating consequences for the planet and everything and everyone depending on it (Earth overshoot day, 2021).

3.1.2. Construction and demolition waste (CDW)

As explained in the previous section, a significant part of the global energy consumption and CO2 emissions are related to the building industry and the main sources of emissions in the building industry are production, operation, and demolition. Construction, and demolition activities generate tremendous amount of waste and for Europe it was reported that the construction industry represented 35,9% of the total waste generation in 2018 (Figure 4) (Eurostat, 2018).

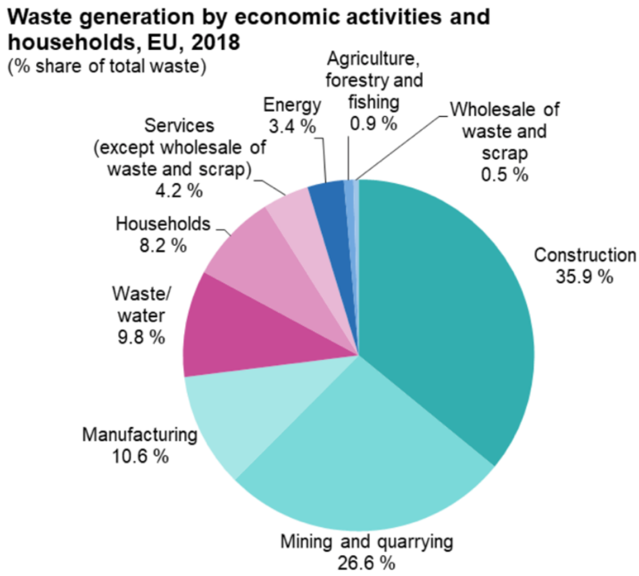

Figure 4 - Waste generation by economic activities and households (Eurostat, 2018).

A study done by the Waste Resources Action Program in 2016 revealed that for Great Britain, 37% the total material input is *lost* during use (WRAP, 2019). In Norway, data from Statistics Norway indicate that of the 2,1 million tons of waste produced, almost half of this amount comes from the demolition of existing structures (Table 2). While the waste management of new construction is moving in a positive direction comparing 2019 and 2020, quite the opposite can be observed for the demolition activities, with a relative increase of 22,9% from 2019-2020 (Statistics Norway, 2021).

Table 2 - Construction and demolition waste in Norway (Statistics Norway, 2021).

	Tons 2020	**Amount in % 2020**	**Change in % 2019 - 2020**
Construction in total	2 135 747,00	100 %	9,6 %
New construction	646 742,00	30,3 %	-1,7 %
Rehabilitation	510 806,00	23,9 %	3,3 %
Demolition	978 200,00	45,8 %	22,9 %
Updated 31st of March 2021.			

The EU Directive Guidelines for Waste Management are a part of the EEA (European Economic Area) and has set as a criterion that 70% of the total non-hazardous waste should be redirected to reuse or recycling in 2020 (Appendix II – Criteria based on the EU taxonomy). In 2019 Norway managed to reach a reuse and recycling share of only 46%, a percentage quite lower than the goal defined by the EU.

3.1.3. Lifespan of buildings

In present design of buildings there is usually established a lifespan goal for the design- and service lifetime of the structure, e.g., with minor upgrades a school or theater should have a lifespan of at least 60 years. Consequently, this creates a demand for the structural members to have a service lifetime corresponding to the period of the entire building (table 3) (International Organization for Standardization, 2017).

Table 3 –Lifetime of building components according to ISO 15686-5:2017 (International Organization for Standardization, 2017)

Expected lifetime of the building	**Components that are hard to reach or structural members**	Components where upgrades are difficult or expensive	Large but easily changeable components	Technical installations
Unlimited	**Unlimited**	100 years	40 years	25 years
150 years	**150 years**	100 years	40 years	25 years
60 years	**60 years**	60 years	40 years	25 years
25 years	**25 years**	25 years	25 years	25 years
15 years	**15 years**	15 years	15 years	15 years
10 years	**10 years**	10 years	10 years	10 years

In Norway, there are several categories for *lifetime,* and they are considered different accordingly (Byggordboka, 2017):

- Aesthetic lifetime: the time a building component is satisfying aesthetic criteria.
- Operational lifetime: the time a building supports the practical use of the building.
- Technical lifetime: the time a building or building component is satisfying the expected technical function of use.
- Economical lifetime: the time a building or building component is used before it must be changed, refurbished, or demolished.

In a global study performed by Structural Xploration Lab at Swiss Federal Institute of Technology, a total of 193 demolished medium and low-rise buildings were investigated. The height varied between 20-215 meters and the year of construction was from 1885 to 2009. Results showed that the average lifespan of all demolished buildings was 39.1 years (Muresan, 2020). Data from Statistics Norway shows that the average lifespan of buildings in Norway (table 4) is close to the global results obtained by Muresan. Note the short lifetime of industrial buildings. These are structures that has considered obsolete while still having a lot of embedded potential.

Table 4 - Economical lifetime of buildings in Norway (Statistics Norway, 2018).

Average economical lifetime (years)						
Category	**Number of cases**	**Avg**	**Min**	**Max**	**Std dev**	**Var coeff.**
Hotels, tourism housing mv.	15	**53,2**	5	100	31,8	0,6
Other buildings	307	**28,1**	3	100	15,5	0,55
Industrial buildings	153	**15,3**	3	50	8,2	0,54
Commercial buildings	110	**59,4**	5	100	27,7	0,47
Technical installations in buildings	99	**16,8**	5	50	9,2	0,55

Demolition is often the result of either two reasons: structural damage or functional obsolescence. Buildings suffering from structural damage have either been affected externally (e.g., fire, earthquake, storm etc.) or the damage can result from bad maintenance, material degradation or bad structural design. Functional obsolescence concerns buildings that need to make way for new developments, free land, are unfit for its purpose or simply abandoned because of relocation of business or other reasons. In a recent study of demolished buildings, findings showed that in only 14% of the cases the building was demolished because of insufficient structural integrity (figure 5) (Muresan, 2020).

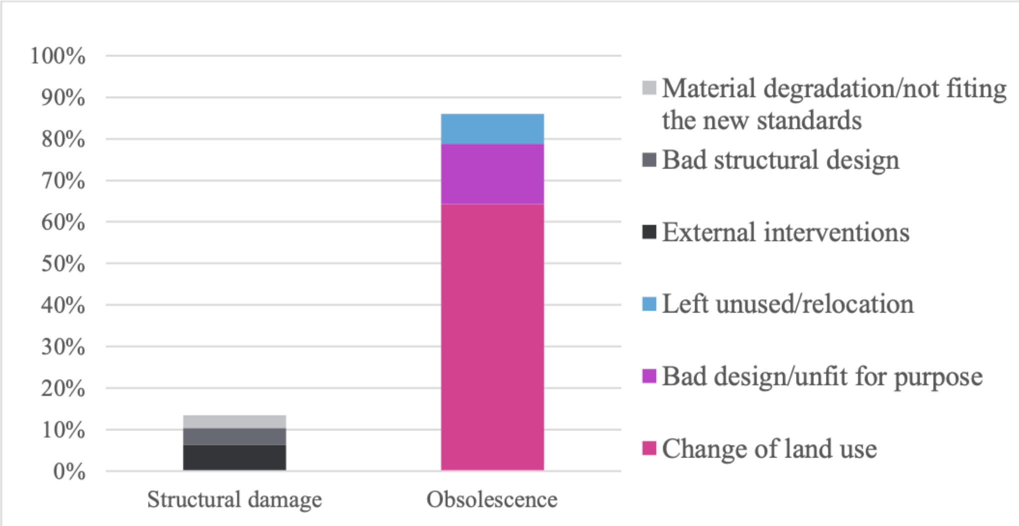

Figure 5 - Reason for demolition of the 193 studied buildings (Muresan, 2020).

A structural system usually consists of a light structure (e.g., timber or steel frames) or a heavy structure (e.g., concrete beams, columns, and slabs). Both systems are both a major part of the total mass in a structure.

3.1.4. Modern tools for sustainable building design

In the last twenty to thirty years, it has globally been a growing attention on environment and sustainability. This has highly affected how the building industry has developed. During this period, there have been introduced several tools and guidelines to steer the practice in the direction of a greener building industry. LEAN or LEAN-Production had a breakthrough in the 1990´s and made one of the biggest impacts on efficiency of production and distribution since the revolution of the assembly line production in 1911 at Ford Motor Company (Britannica Group, 2021). LEAN production is about eliminating waste from the production process and at the same time increasing efficiency by replicating product design and minimizing storage time of products (LEAN Production, Vorne Inc., u.d.). An example of LEAN production is the production of prefabricated concrete elements.

After the introduction of LEAN, the first versions of certification manuals such as BREEAM (Building Research Establishment Environmental Assessment Method) and LEED (Leadership in Energy and Environmental Design) were established. They are both systems to verify that a building is designed to improve performance across metrics such as energy savings, water efficiency, CO2 emissions reduction, improved indoor environmental quality, and stewardship of resources (U.S Green Building Council, 2020). BREEAM is the preferred method used in Norway, and it is continuously developing to implement more aspects of the building industry, e.g., reuse scenarios. The manual works as a certification system where a project first needs to qualify by satisfying the criteria in the legislation (TEK17) and a set of basic demands defined in the BREEAM manual. After these criteria are met, the project can qualify for x-number of points freely within the 10 focus areas of the manual (figure 6). Depending on the number of points, the project is eventually assigned a final score which results in a certain grade (figure 7).

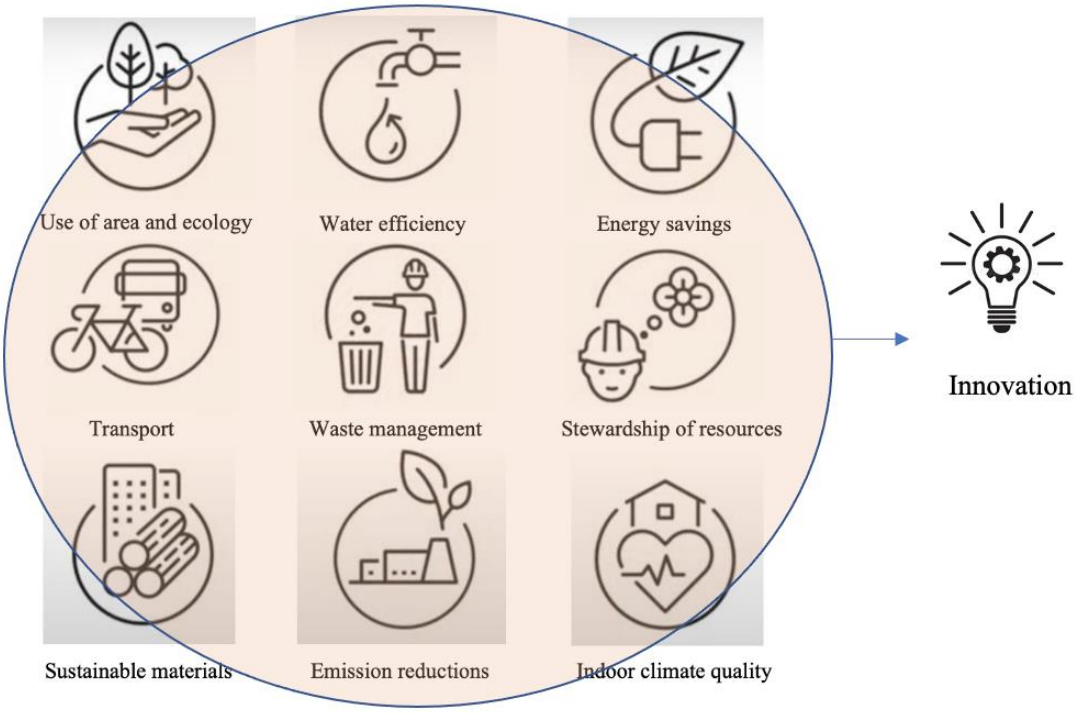

Figure 6 - Ten focus areas in BREEAM-NOR v.6.0

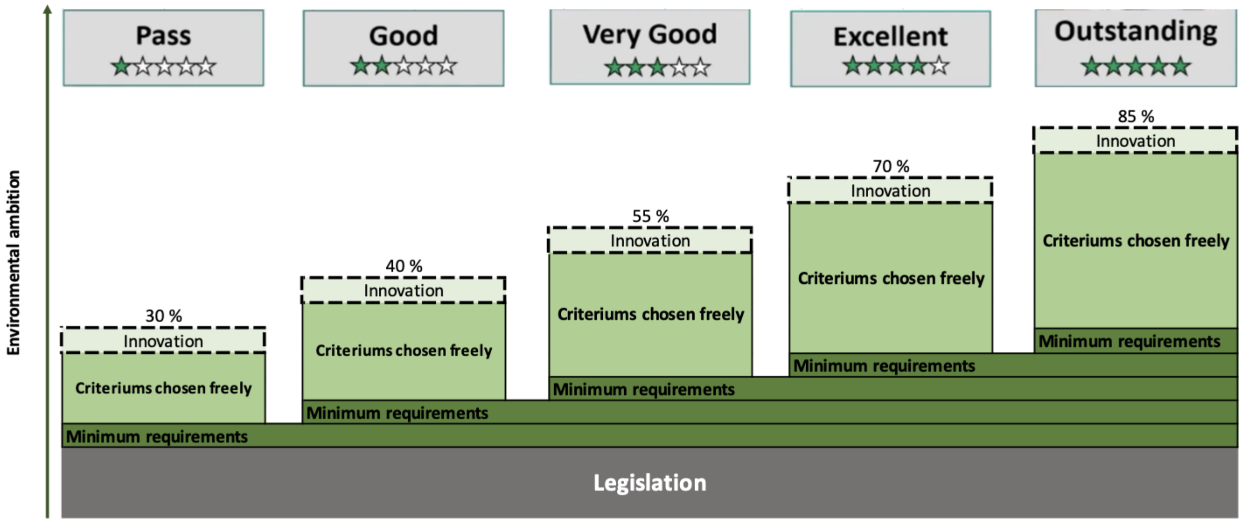

Figure 7 - BREEAM-NOR grading system. Percentage represents the share of points that is needed (Curtesy: Norwegian green building alliance)

BREEAM was created especially for the British building sector and was until 2010 not used much in Norway (Arkitektnytt, 2022). An important reason for eventually introducing BREEAM over LEEN was that the latter did not allow for national adjustments and additions. Most recent is the BREEAM-NOR v6.0 manual which has included reuse and DfD as a key aspect in the sustainable design of new and existing buildings (Norwegian green building council, 2022). The BREEAM-NOR v.6.0. contains more details on the significant changes and their potential impact, this is presented in the state-of-the-art section in chapter 4.

The BREEAM manual has from 2013 included LCA (life cycle assessment) in their schemes. LCA is used to total up the environmental impact based on data that depends on the product's composition and supply chain. LCA can be used to work out the environmental impact of almost anything, from a can of beans to a car and to an entire building. To calculate these impacts LCA takes information about each product as input, this information is stored in a document known as an EPD (environmental product declaration) (Building Reserch Establishment, 2018). The governing standards in LCA state:

"*The purpose of an EPD in the construction sector is to provide the basis for assessing buildings (…) and identify those which cause less stress to the environment*" (Building Reserch Establishment, 2018). By gathering all the known products and their quantity from a building, the designer can introduce this information in an LCA calculation tool such as One-Click LCA and your output will be the total environmental impact for the life cycle of a single element or a total project. By linking the digital EPD to the related component in a BIM this reduces the need of manual work further. That is because the digital twin (BIM) can be uploaded and processed so that the information and quantities of each component are read and understood correctly. This results in a very accurate environmental impact of the total life cycle (OneClick LCA, 2021).

3.2. Recycling

The 3 R´s were mentioned earlier as an important part of CE. These actions can also be recognized in the waste hierarchy used by the European Commission in their waste prevention and management strategies (figure 8) (European Commission, u.d.). The best practice reducing waste is preventing the creation of waste itself. Reuse is considered the next best option and before recycling and disposal are listed respectfully. Reuse and the opportunities related to it will be discussed in depth later in this thesis. Recycling can be defined as:

"A process where the material goes through mechanical or chemical transformations to find a new purpose of use" (Fivet & Brütting, 2020). Unlike reuse where the component keeps it original value and intended purpose, recycling leads to a downgrade in the material utilization value, e.g., a concrete slab is crushed to be used as aggregate. This example shows that there is a change in the use of the material, but it has not been used new material to fulfill the new purpose. In other words, the resource is kept within the material loop, which is a base concept in the CE way of thinking, but the value of utility has decreased (Ellen Macarthur Foundation, 2020).

Figure 8 – The waste hierarchy (European Commission, u.d.)

One can calculate the net flow of materials in a system (M_{net}) by subtracting all content of secondary material of the product at fabrication from the output material flows at the end-of-life of the product (i.e., recovered steel), as in formula 1. Here the amount of recovered material used in the manufacturing of the product is the input flow M_{in}, while the amount of steel to be recovered at the end-of-life of the product is the output flow to the calculated system M_{out} (Girão Coelho, et al., 2020).

$$M_{net} = M_{out} - M_{in} \quad [1]$$

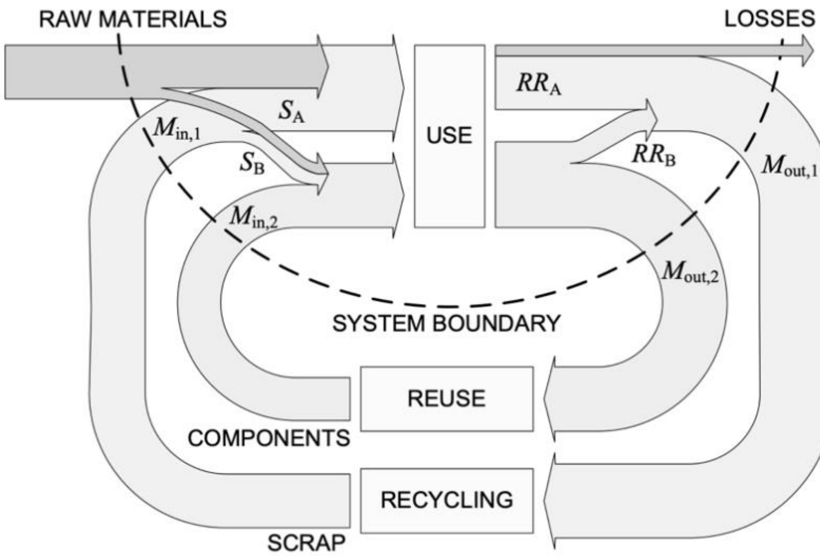

Figure 9 - Illustration of material flow considering production, reuse, and recycling (Girão Coelho, et al., 2020)

Figure 9 illustrates material flows relevant to recycling and reuse of materials. The input of recycled material ($M_{in,1}$) includes material used for new component production (S_A) and material needed to repair and re-manufacture reused components, (S_B). Similarly, the waste output ($M_{out,1}$) is composed of recovered material from the demolition waste (RR_A) and reusable components that are not reused (RR_B) (Girão Coelho, et al., 2020).

3.3. Reuse

3.3.1. Concept of reuse

Reuse is as the name states, a way of taking an object or system and use it again for a different purpose or relocated somewhere else. Across many industries and sciences, we can see the rising focus on reuse, both when it comes to day-to-day actions in the society (e.g., secondhand shopping of clothes) or large-scale reuse in the industry (e.g., reuse of mechanical components such as car parts) (MacArthur, 2020). The main and the most obvious advantage of reuse is that by reusing a product instead of virgin production, both economic and environmental benefits can be obtained. The building industry is now experiencing a shift into a circular economy, and reuse is a hot topic because of the possible climatic benefits that the process possesses (M-ERA-NET, 2020). However, reuse is not a revolutionary way of thinking in the construction business.

3.3.2. Upstream reuse

In a historical perspective, reuse is not at all a new concept in the building industry. One such example is from the 8th century in Cordoba, Spain, where they used columns from nearby ruins of Roman buildings to gather the 142 marble columns supporting the Moorish double arches in the Mezquita (figure 10). This concept of reuse is often referred to as *upstream reuse* and is based on harvesting materials from abandoned, obsolete or soon-to-be-demolished buildings or infrastructure (Fivet & Brütting, 2020).

Figure 10 - Moorish double arches inside the Mezquita. Cordoba, Spain (InSpain News, 2021)

Upstream reuse was a common practice prior to the industrial revolution because it was more cost and time efficient than new production. After the industrial revolution, machines, explosive growth of population and tendencies of urbanization made the prices for labor and material go down and the need for buildings and infrastructure increased (Fivet & Brütting, 2020). As a result, reuse became far less practiced, and the development of knowledge related to reuse stagnated. Consequently, this led to a huge void in the practice of reuse, but in recent times the practice has reemerged because of the climatic benefits.

There are as of today modern examples of upstream reuse in the built environment. Kristian August Gate 13 (KA13) in Oslo is a modern example of upstream reuse (figure 11). KA13 is a rehabilitation project where many of the newly introduced elements are harvested from other buildings, old parts of the existing building, or are collected from material banks of incorrectly produced elements for other projects. Of all the introduced materials, 80% are categorized as reuse. For the rehabilitated construction it was introduced 64 tons of steel, of which 45 tons were shaped and reused from a stock of 57 tons of reused steel. This resulted in a reuse-grade of 70% in the new steel frame structure (figure 12). By cutting and shaping of the reused elements the project ended up with 12 tons of waste which could be sent to recycling (Entra ASA, 2021).

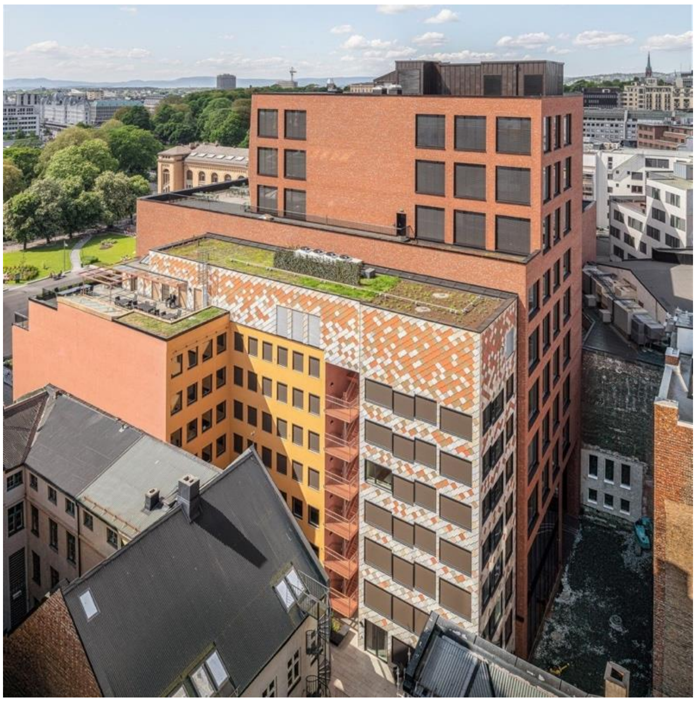

Figure 11 - Kristian Augusts Gate 13 (Asplan Viak, 2022)

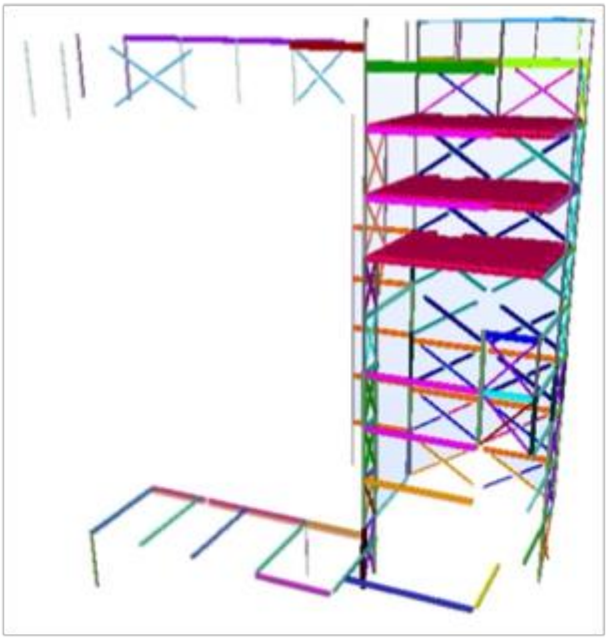

Figure 12 - Illustration of reused elements in the steel frame of KA13 (Entra ASA, 2021)

In cases where future reuse in considered prior to the original design, it can be said that a principle of *downstream reuse* is implemented (Fivet & Brütting, 2020).

3.3.3. Downstream reuse

Downstream component reuse sets fundamental criteria for easy repair, possibility for replacement, disassembly, transport and eventually reassembly. The concept should neither constrain the possibility to a change of geometry nor the capability to take a variety of different load paths. Historically this method was more common for *temporary structures*, one example is from Switzerland where the same timber elements was used for temporary framework and scaffoldings for two different bridges (figure 13). Most special about this case was that the timber members consisted of only two different crossections and one single dimension of bolts, but still maintaining dynamic enough to take the shape of different structures (Fivet & Brütting, 2020).

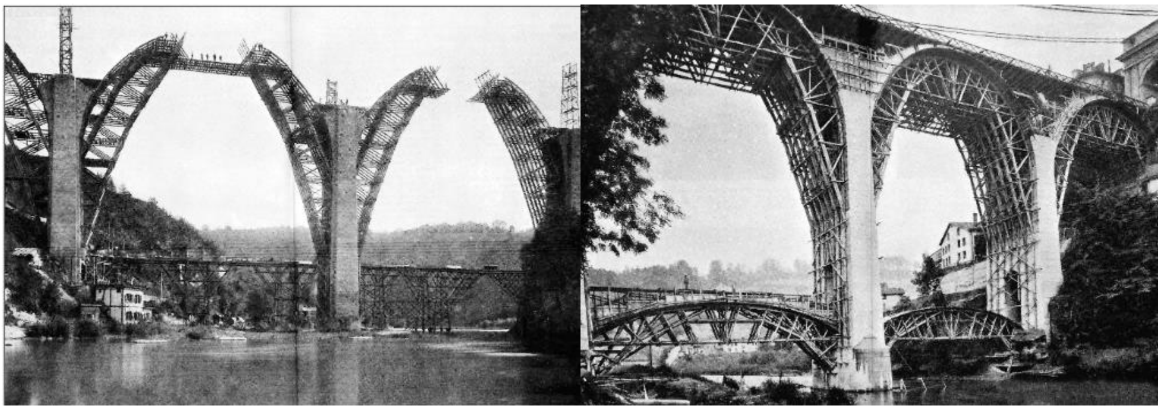

Figure 13 - Same timber elements used for Pérolles in 1921 (left) and then Zärhingen in 1924 (right). (Fivet & Brütting, 2020).

Another historical example of downstream reuse is the Nordic building method *laft*. Here timber logs are precut, and ends are shaped so that the logs can be joined and stacked to create a stiff and relatively airtight structure. The modular building method made the elements changeable, and the entire structure suited for disassembly and possible to relocate (Norwegian Digital Lexicon, 2021). Figure 14 shows a laft-woodshed with timber logs, some tracing all the way back to the year 1166 (hallingdolen.no, 2017).

Figure 14 – A partially restored woodshed in Uvdal, Norway. Photo credit: Torbjørn Gunhildgard (hallingdolen.no, 2017)

Even though there are good historical examples of reuse of different types of material, there is still very little downstream reuse of structural members in the practice today. The reason for this is not ambiguous and there are several factors restraining the potential of reuse, such as structural norms, logistics, health related and lack of standardization. Still, the building industry has come to realize that to limit their major climatic impact, the renaissance of reuse is paramount. A part of the solution is to develop methods based on the same concept used in laft and make it applicable to advanced structural design. The scientific community agrees that designing buildings that can be disassembled and reused, as a whole or redistribute only parts of the structure, is a key aspect of reducing the future carbon footprint of the industry (Rakhshan, 2021). This method has been commonly known as DfD (design for deconstruction).

3.4. Design for deconstruction

Design for deconstruction is not a new concept in the practice of building design, but because of the growing realization of its environmental benefits, the technique is now going through a revolution. The industry is in short of guidelines and is requesting a commonly accepted framework with methods and tools for a systematic and transparent assessment of the potential for a second life of building components and systems (M-ERA-NET, 2020). In 2020 the International Standard Organization (ISO) published a booklet of eleven documents providing guidelines for sustainability in construction works. One of these documents (**ISO 20887 - Sustainability in buildings and civil engineering works - Design for disassembly and adaptability - Principles, requirements, and guidance**), are dedicated to DfD and in this ISO declares:

"*Applying the principles of design for disassembly and adaptability (DfD/A) to the service life planning of buildings and civil engineering works can make a positive contribution to sustainable development. While service life planning is a design process that seeks to ensure that the service life of a constructed asset will equal or exceed its design life, DfD/A is a strategy to optimize both the service life and the design life. The strategy does not suggest overbuilding to meet a vast number of unknowns that a constructed asset might encounter*." (ISO, 2020). With this ISO suggests that DfD should be practiced within reasonable boundaries.

The fundamental concept of DfD is to design a structure that can be industrially produced, constructed, disassembled, and reused to the same or different purpose without major processing and staying inside the material loop (figure 15) (Rakhshan , 2020). Based on these criteria it is obvious that a decisive part of the design is that the members can be deconstructed (taken apart) without being damaged. A consequence of this is that monolithic connections need to be avoided whenever possible (Webster, 2005).

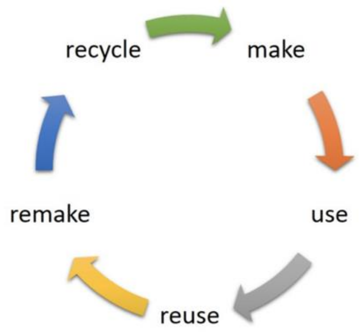

Figure 15 - Illustration of a circular economy that keep materials in the loop (Archdaily, 2022)

In basic terms the goal of DfD can be reduced into three main objectives (Abuzied, 2020):

1. Simplifying the de-manufacturing process
2. Reducing needed time and cost for disassembly
3. Allowing recovery of components and materials

While the principles of DfD might seem simple, the practice depends on techniques and methods very different from the traditional structural design. In the report *Design for deconstruction and reuse of timber structures – state of the art review,* presenting innovative design for the future published by the ERA-NET funded organization InFutUReWood, it was presented a set of guidelines that is recommended to assess in designing for deconstruction (table 5). The guidelines also distinguish between the purposes of the suggested measures, in other words if the measures are to improve the elements disassembly abilities or if they are meant to increase the reusability (M-ERA-NET, 2020).

Table 5 - List of measures suggested to be followed for a DfD-design (M-ERA-NET, 2020)

Measure to be done	Disassembly	Reuse
Minimize the number of different types of components	x	x
Use mechanical not chemical connections	x	
Use an open building system not a closed one		x
Use modular design		x
Design to use common tools and equipment, avoid specialist plant	x	x
Separate the structure from the cladding for parallel disassembly	x	
Provide access to all parts and connection points	x	
Make components sized to suit the means of handling	x	
Provide a means of handling and locating	x	
Provide realistic tolerances for assembly and disassembly	x	
Use a minimum number of connectors	x	
Use a minimum number of different types of connectors		x
Design joints and components to withstand repeated use		x
Allow for parallel disassembly	x	
Provide identification of component type		x
Use prefabrication and mass production	x	x
Use lightweight materials and components	x	
Identify points of disassembly	x	
Retain all information of the building components and materials		x

Even though DfD is still not a common practice, an increasing number of architects, engineers, and builders are trying to include this concept in their designs. A good example of this is a 4-storey commercial mass timber building designed to be deconstructed and fully reusable (figure 16).

Figure 16 – Reusable commercial building in CLT and glulam (OsloTre, 2021).

Figure 17 - Illustration of mechanical connectors used in project HasleTre (OsloTre, 2021).

A key aspect of the design was to use mechanical connections that are easily accessible (OsloTre, 2021) (figure 17).

3.5. Quantification reuse and recycling potential

LCA, LCC, BREEAM, LEEN, among others have previously been introduced as different tools to evaluate the climatic impact of a building- or other infrastructure project. As explained in section 3.1.4 a complete and accurate life cycle analysis can be performed with software programs such as OneClick LCA. It has been stated by designers and planners that a big issue regarding these calculation tools and guidelines is that quantifying the reuse-potential is challenging (Rakhshan, et al., 2021). This further affects the regulatory aspect because it becomes unclear how incentives should be introduced. In the report presenting recommendations for reuse on the behalf of the steel industry in Europe, it is introduced a suggestion on how the reuse-potential can be quantified (Girão Coelho, et al., 2020):

The total impact of for example cost, specific emission, or resources is associated with formula 1, and is calculated considering the impact of material recovery (χ_{MR}) by subtracting the impacts for acquisition and pre-processing of virgin material (χ_{VM}). The impact of virgin material is calculated from the cradle to the point of functional equivalence, where virgin material can be established as a constituent product, component, or assembly. Then the total impact can be expressed as in formula 2

$$\chi = M_{out}(\chi_{MR,out} - \chi_{VM,out}) - M_{in}(\chi_{MR,in} - \chi_{VM,in}) \qquad [2]$$

The net amount of substituted virgin material can be different from the amount of recovered secondary material and therefore the net flow may be reduced by the yield factor Y representing the *efficiency* of the recovery process. Moreover, if the product is downcycled or has a limited number of reuse cycles, the impact of substituted primary production may be reduced by quality factors of the secondary (recovered) and virgin material; Q_{MR} and Q_{VM} respectively. Including the factors, we extend formula 2, resulting in formula 3.

$$\chi = M_{out} * Y\left(\chi_{MR,out} - \chi_{VM,out}\frac{Q_{MR,out}}{Q_{VM,out}}\right) - M_{in} * Y\left(\chi_{MR,in} - \chi_{VM,in}\frac{Q_{MR,in}}{Q_{VM,in}}\right) \qquad [3]$$

Assuming that the unit impact of the primary production and recovery process are the same at the beginning and at the end of a product´s life, the expression can be simplified as formula 4. This has a few chances of occurrence but as a simplification it is considered accurate enough.

$$\chi = (M_{out} - M_{in}) * \left(\chi_{MR} - \chi_{VM}\frac{Q_{MR}}{Q_{VM}}\right) * Y \quad [4]$$

When the input flow of the existing product is more efficient than the recovery at the end-of-life stage, formula 3 and formula 4 produce a positive number. This means that the impact X is an overall burden. If the existing product has a low recovered material content and it is recovered efficiently at the end-of-life, the impact X is a benefit (negative number).

If two or more recovery processes are assessed at the same time, it is recommended to extend formula 4, yielding formula 5. Here the flows of each secondary material are treated separately.

$$\chi = \sum (M_{out,i} - M_{in,i}) * \left(\chi_{MR,i} - \chi_{VM,i}\frac{Q_{MR,i}}{Q_{VM,i}}\right) * Y \quad [5]$$

Formula 5 can be calculated for recycling and reuse streams separately as in formula 6 with the indexes 1 and 2 for recycling and reuse respectively.

$$\chi = (M_{out,1} - M_{in,1}) * \left(\chi_{MR,1} - \chi_{VM}\frac{Q_{MR}}{Q_{VM}}\right) * Y_1 + (M_{out,2} - M_{in,2}) * \left(\chi_{MR,2} - \chi_{VM}\frac{Q_{MR}}{Q_{VM}}\right) * Y_2 \quad [6]$$

The recovery process efficiency of reuse (Y_2) will always be 1,0 and can therefore be neglected. In the case of steel recovery, quality factors (Q_{MR} and Q_{VM}) can be neglected because the recycled steel obtain approximately the same qualities as virgin steel. The yield factor (Y) is relevant only for the scrap recycling. It is recommended to use Y_{steel} = 0.916 according to the World Steel Association (World Steel Association, 2017).

In 2015 90% of the wood-based waste from construction in Norway was used in energy recovery processes and 8% was recycled and reused in new products, often with a lower operational value (e.g., fiber plates or insulation materials) (NIBIO, 2018). This corresponds to the findings done in a wood waste study conducted by Arnaud Hoennige in 2018. The findings of Hoennige showed that CDW (construction and demolition waste) is often of higher quality than many other wood-waste types. Since this thesis focus on construction materials, this can therefore help to upscale the yield factor. Though, recycled wood waste often experiences a downgrade in material value for every time it is recycled. This is not the case with steel which can maintain almost the identical properties through several life cycles. The study also revealed that by applying already existing techniques the utilization of CDW could be improved. This means a reduction of the share of wood waste used in energy recovery and an increase in reuse and recycled products (figure 18). Hoennige also point out that over the last decades the total forestry volume in Norway has been increasing (Hoennige, 2018). Even though the value is only accessible once, one should consider the energy recycling potential of timber products. Yield factor (Y) for recovery of timber is related to a high degree of uncertainty depending on the recycled component and its material quality, making it difficult to define a precise value.

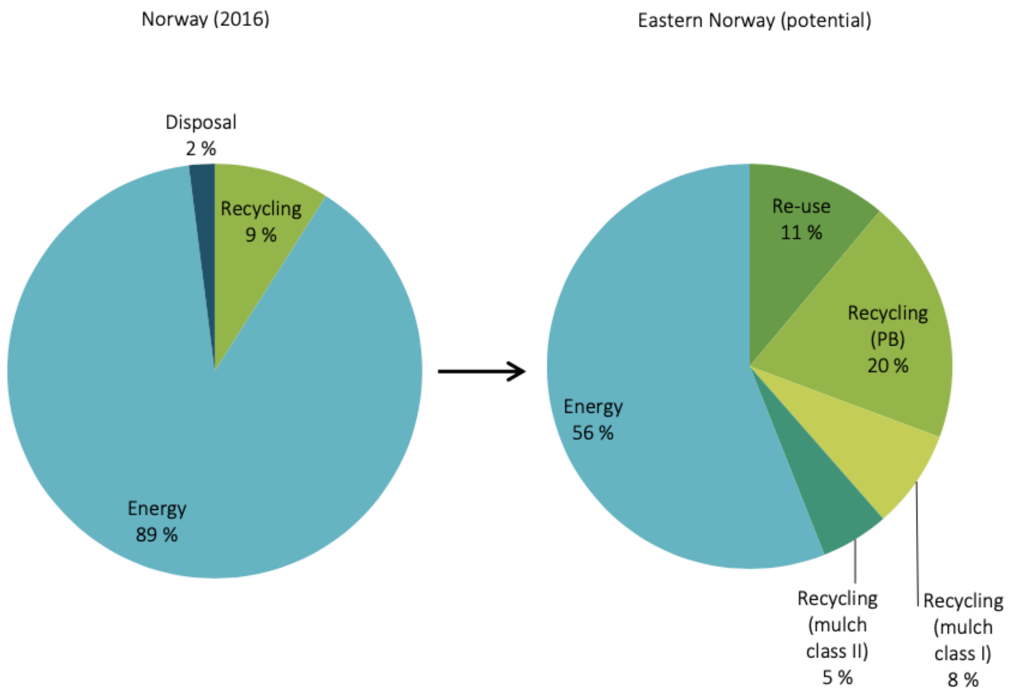

Figure 18 - Wood waste management in Norway in 2016 (left) and potential wood waste management in Eastern Norway (right) (Hoennige, 2018).

In the study performed by Gebremariam the focus area was innovative technologies for recycling end-of-life concrete waste. The results were promising and showed that the most circular concrete which consisted of 80% of recycled aggregates, had good structural applications (Gebremariam, 2020). Still, the practice is rarely used, and the recycling of concrete today usually result in materials for backfilling operations. This is a significant reduction of the material value. Concrete does however, experience very little material degradation compared to timber. This means that crushed concrete can theoretically be used as aggregates or backfilling through several life cycles, improving the yield factor. As with timber, the uncertainty regarding the downgrading of material value makes it is difficult to define a precise yield factor (Y).

3.5.1. Numerical example (steel)

CEN/TC 350 – Sustainability of Construction Works is a set of standards compiled up to create a standardized process for environmental building assessment. Through these standards a reference framework is presented along with horizontal standardized methods for assessing the environmental performance on both new and existing buildings (Anon., 2022). Based on the standards in this set, the life cycle information can be divided into five stages:

- A1-3 (Product stage)
- A4-5 (Construction process stage)
- B (Use stage)
- C (End-of-life stage)
- D (impacts beyond the system boundary, e.g., reuse)

These mentioned stages can be divided into even more specific processes as illustrated in figure 19.

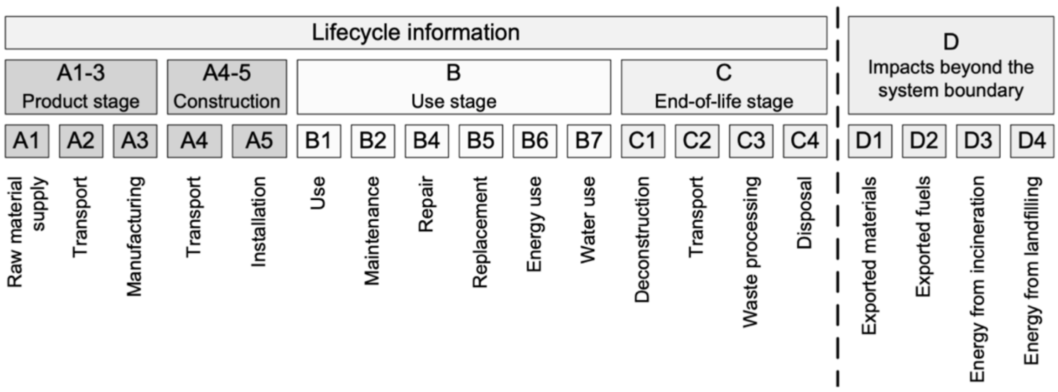

Figure 19 - Life cycle stages NS-EN 15804. (Standard Norway, 2019)

EN 15804 divides the *impacts beyond the system boundary* (D) into four sub-modules. Module D1 consist of burdens and benefits related to the export of secondary materials. The calculation the impact of $\chi_{\text{module,D1}}$ in EN 15804 is presented in formula 7. The environmental impact of the substituted virgin material $\chi_{\mathrm{VM,sub,out}}$ is reduced by the ratio of the quality factors of the recycled and substituted virgin material $Q_{\mathrm{R,out}}/Q_{\mathrm{sub}}$ (Standard Norway, 2019).

$$\chi_{moduleD1} = \sum (M_{MR,out,i} - M_{MR,in,i}) \left(\chi_{MR,after,,out,i} - \chi_{VMSub,out,i} * \frac{Q_{R,out}}{Q_{Sub}}\right) \quad [7]$$

In the case of constructional steel, it is recommended to neglect the quality factors ($\frac{Q_{R,out}}{Q_{Sub}}$ =1) but to consider yield of secondary steelmaking as:

$$M_{MR,out,1} = M_{out,1} * Y$$

And

$$M_{MR,in,1} = M_{in,1} * Y$$

GWP (global warming potential) is one of the specific emissions reported in the EPD and its value in lifecycle stages A to C is called "carbon footprint" of the product or building in $kgCO_{2e}$. In this example, the unit impacts of product stage $\chi_{\mathrm{module,A1-A3}}$ are based on the virgin material production, recycling, or reuse. Recycled and virgin material production has a unit impact of 0,636 and 2,17 kgCO2e/kg respectfully and both have an additional impact for transport and manufacturing of 0,25 $kgCO_{2e}/kg$ (modules A2+A3) (table 6). Reuse is 0 $kgCO_{2e}/kg$ in the modules A1-A3 (World Steel Association, 2017). The impacts used have been controlled against an EPD for steel sections provided by a Norwegian producer and the values are corresponding (Norwegian EPD foundation, 2021). GWP of the construction stage (A3+A4) is estimated as $50tCO_{2e}$, and the impact $e_{\mathrm{module,C}}$ of deconstruction is estimated at 70 tCO_{2e}. The reason for this is that deconstruction is more laborious than the construction since cleaning and separation of the components is a time consuming but necessary part of the process. The use of e_{moduleB} is not considered in this example because it is expected a short service life without specific maintenance requirements, meaning that the value will be equal for both categories and can therefore be neglected.

Table 6 - GWP unit impacts (EN 15804)

Global warming potential according to EN 15804				
	Unit impacts used in the example			
	Recycling [kgCO2e/kg]		Reuse [kgCO2e/kg]	
Unit impact of the recovery process [a]	$\chi_{MR,1}$	0,636	$\chi_{MR,2}$	0
Unit impact of the substituted primary production [b]	χ_{VM}	2,17		-
[a] 0,386 $kgCO_{2e}/kg$ (A1) plus 0,25 $kgCO_{2e}/kg$ (A2+A3)				
[b] 1,92 $kgCO_{2e}/kg$ (A1) plus 0,25 $kgCO_{2e}/kg$ (A2+A3)				

In this example it is assumed a material flow for a hypothetical steel-framed building. The steelwork has total mass 100 tons and is fabricated from 10 tons of reused steel sections and 90 tons are steel from the steel mill. The scrap used in the steel mill for production of 90 tons new steel is set to 55 tons (close to the EU average). Due to the losses of steel in recycling, 55 tons of scrap represent only 50.4 tons of the final products (yield factor of 0.916 according to (World Steel Association, 2017)) and the remaining 39.6 tons must be produced from raw materials. It is estimated that 30 tons of the steelwork can be further *reused* after the project´s end-of-life. Finally, 5 tons of the steel will be lost or discarded at the end of life, and the rest will be sent for recycling. The calculation parameters are presented in Table 7.

Table 7 - Material flow in a hypothetical example

Material flows of recycling and reuse				
	Recycling [tons]		Reuse [tons]	
Input of secondary material	$M_{in,1}$	55	$M_{in,2}$	10
Output of secondary material	$M_{out,1}$	65	$M_{out,2}$	30
Efficiency of the recovery process	Y_1	0,916	Y_2	1,0

The material flows (table 7) and unit impacts (table 6) yield the following results for the life cycle stages. Formula 8 represent the material flow regarding secondary material utilization grade.

$$M_{MR,out,1} = 65 * 0{,}916 = 59{,}5\ t \qquad and \qquad M_{MR,in,1} = 55 * 0{,}916 = 50{,}4\ t \qquad [8]$$

Formula 9 expresses the global warming impact of recovery of secondary material and new production.

$$e_{module,A1-3} = \sum M_{MR,in,i} * \chi_{MR,i} + M_{VM,in} * \chi_{VM}$$
$$= 50{,}4 * 0{,}636 + 10 * 0 + (100 - 50{,}4 - 10) * 2{,}17 = 88{,}1\ tCO2e \qquad [9]$$

Formula 10 expresses the potential benefit after end of life whereas the quality factors are neglected.

$$e_{module,D1} = \sum (M_{MR,out,i} - M_{MR,in,i})(\chi_{MR,i} - \chi_{VM})$$
$$= (59{,}5 - 50{,}4)(0{,}636 - 2{,}17) + (30 - 10)(0 - 2{,}17)$$
$$= -57{,}5\ tCO2e \qquad [9]$$

Then the whole life cycle impact (carbon footprint) of the building is the sum of the modulus A, B and C. It is 88,1+50+0+70 = 208,1 tCO2e with the potential to *save* 57,5 tCO2e (modulus D) in the next lifecycle. The potential savings are making up over 25% of the carbon footprint of the whole life cycle.

If this example were to be performed with timber or concrete the share of primary production with virgin materials would be remarkably higher because of the much lower yield factor (Y).

3.6. CE and reuse

3.6.1. Status quo

Climate has changed over the last decades and there has been a change in global temperatures and in the occurrence rate of extreme weather. The use of historical data and advanced climate modelling tools have led to a common understanding in the scientific community. It is consensus among researchers that if the emissions are not reduced drastically, the average temperature will rise above a critical level and lead to fatal consequences for humans, nature, wildlife, and the world in general. This increase in average temperature is defined as *global warming* (The European Comission, 2021). To limit the increase of average temperatures a total of 196 parties (countries) signed at the Conference of the Parties in Paris the legally binding international treaty called *The Paris Agreement*. The treaty states that the parties oblige themselves to limit global warming to well below 2 degrees, and preferably below 1,5 degrees, compared to pre-industrial levels. To achieve this goal the net emissions, need to be around zero by the year of 2050, indicating a big need for reduction of emissions and the development of effective carbon capture. The meeting took place in December 2015 and the treaty entered into force in November 2016 (United Nations, 2020).

Every five years there is a milestone and a review of the current situation. The progress of 38 countries is being tracked by the Climate Action tracker, an independent scientific research group. The analysis is using current data and the individual goals of each country to rate their relative contribution to reduce global warming. According to their recent findings, few countries that are likely to provide their contribution to reach the well below two degrees increase in temperature. During the period writing this thesis, only the United Kingdom from the European countries was considered likely to reach the goals set by the Paris Agreement (Climate Action Tracker, 2022). Norway is currently being rated as insufficient and it is stated that policies and action plans are one of the aspects deviating furthest away from the benchmark goals. This could imply that Norway is presenting climate action plans that are too passive and should make adjustments to reach the goals. It should be mentioned that this assessment was made 30th of July 2020 and Norway published a renewed climate action plan in 2021 (Norwgian Government, 2021).

On the behalf of the Norwegian Government, the international consultant company Deloitte created a report to serve as a theoretical foundation in developing the new strategy to shift into a circular economy. In the report it is stated that the construction industry is one of the sectors with the highest potential to increase the level of circularity, pointing out the following area of improvement to be the most important

"*Increase the use of materials that are suited for repair, dismantling, reuse, and recycling*". The enormous amounts of waste and use of virgin materials were pointed out as a basis for their conclusion (Deloitte, 2020).

The European Union has stated in their action plan for circular economy that the building and infrastructure sector plays a key role in implementing CE (The European Union, 2021). The Norwegian Government has also made this statement in their climate plan from 2021-2030 and further states that reducing waste and reusing more is a salient point in reaching the goals for reduced GHG emissions. (Norwgian Government, 2021). As an addition to just encourage the building industry to become more environmental-friendly by stating the climatic consequences, governmental officials introduce legal acts and financial incentives. Such an example is in the Planning and Building Legislation, where contractors are encouraged to use *best practice**. One such example is where the projects are encouraged to operate with completely fossil-free construction sites within the year of 2025 (The Norwegian Parliament, 2021). There has also been introduced a law binding official and private contractors to pay a CO2-fee on emissions that are categorized as *not a part of the accepted quota* (The Norwegian Government, 2020). This action will introduce a financial incentive to the involved parties, and as in most cases, economic influence has a major impact. The new action plan highlights that the current incentives for sale and distribution of reuse-components are too weak (Norwgian Government, 2021).

*Best practice means that the method or technique used is generally accepted as superior to other alternatives.

3.6.2. Legal acts and legislations

In Norway the most important regulations regarding building products are found in TEK17 and DOK. TEK17 is a document describing technical criteria for the use of building components and are directed against the responsible contractor in the project. DOK is a guideline for the sale and distribution of building components and are directed against producers, importers, and distributors of building products (DiBK, 2021). The purpose of DOK is defined as:

"*The guideline contains demands and regulations of CE-certifications of building materials. CE-certification means that a product has been produced based on a harmonized standard or the producer has chosen to have an official European technical certification of the product*" (DiBK, 2016).

DOK § 10 (Appendix I – Norwegian legislations for the building industry) states that:

"*Fundamental requirements (...) are documented relative to the importance of the component's role in the potential building*". And in addition to this declares that:

"*Fundamental requirements (...) should be documented according to a satisfactory technical specification*" (DiBK, 2016). Along with the CE-certification this is an additional criterion, and such a technical specification can be:

- A national standard
- Technical approval from a third party (e.g., SINTEF)
- Technical specifications from the producer

Based on this there are several ways of obtaining such a technical specification, but as of today there are few standardized testing methods to consider and validate products for reuse (DiBK, 2021). In TEK17 § 2 and § 3 (Appendix I – Norwegian legislations for the building industry) there is criteria for documenting technical performance, but how to obtain this documentation for reused components is unclear (DiBK, 2017).

As mentioned in the previous section, the EU, other European directives, and the Norwegian government are setting guidelines so that the construction industry is motivated to prioritize a circular economy instead of continuing in the path of a linear one. As a way of reaching its goals the Norwegian government defined a set of ambitions that they are to follow in all projects where the state is involved as either contractor, stakeholder, or tenant (Norwgian Government, 2021):

- The government is to exploit existing building mass and secure reuse of vacant properties.
- The government is to reuse building materials and make governmental-owned reusable materials available to the private sector.
- The government is to cooperate with the industry to promote climate-friendly materials and products.
- The government is to establish a common methodology to measure the total climate and environmental impact of properties with a goal of improving this method continuously.
- Governmental departments are to emphasize the environmental rewards of reuse in already regulated and built environments

The report states that a possible economic incentive can be demanding a tax on all GHG emissions over a relative limit. These incentives can motivate designers and builders to make sustainable choices and by this encourage reuse and DfD (Norwgian Government, 2021). TEK17 § 9-5 (Appendix I – Norwegian legislations for the building industry) also present guidelines for making building projects more circular (DiBK, 2017).

3.6.3. Standards and design criteria

To secure quality and a safe design of structures it has been created several standards compiling together as a framework to guide the architect, designer and/or structural engineer. There are two main sources of standards we in Norway rely on.

- ISO, International Organization of Standardization
- EN Eurocode standards. Often supported by a N.A (national annex) specially concerning Norway.

The ISO standards are international and have a big library of standards concerning everything between film, language, environment, and buildings (ISO, u.d.). The Eurocode standards are for European countries and are a set of 10 standards (plus additions) created to provide a common approach to the design of buildings and other civil engineering works (European Comission, u.d.).

The codes provide controls where the components capacity is checked against what limit states that are the governing for a given situation (Standard Norge, 1990).

- ULS (Ultimate Limit State) is a load combination considered to find out how much a component can be stressed with without failing under somewhat normal situations
- SLS (Serviceability Limit State) is a where we also are considering the usability of the component regarding comfort during use, e.g., vibrations of a floor slab.
- ALS (Accidental Limit State) is where we are considering extraordinary load situations such as an earthquake. What separates ALS from the other limit states is that it allows the structure to take permanent deformation and/or critical damage as long as human safety is maintained. This is because the occurrence of these situations is very rare.

These standards contain limited information regarding the reuse of structural components and there are few guidelines on how a structural component can be verified for reuse. In a systematic review on component reuse of structural members performed by Kambiz Rakhshan it was pointed out that reuse of structural components is not a common practice and in the few cases it has been performed, the members are often over dimensioned. This is because the information about characteristics, details, certificates, and/or drawings of the reused components are often unavailable. The review further highlights the lack of traceability, which is essential to get necessary information to certify members for reuse (Rakhshan , 2020). Limit state design has been a common practice for most western countries since the 1970´s and can therefore provide an indication on how members produced after this method were designed originally (Girão Coelho, et al., 2020).

3.6.4. Incentives

The Norwegian government or other actions takers have historically provided no incentives motivating the reuse of building components (Norwgian Government, 2021). ENOVA is a state-owned organization providing knowledge and financial support when it comes to the development of a society of low emissions and clean energy. ENOVA serves support to sectors, whereas the building and infrastructure industry is one of them (ENOVA, u.d.). ENOVA announced the 31st of March 2022 that they have established the first protocol of financial incentives to motivate the reuse of building materials. The aim of the action is to increase the volume of reused building products in the market, develop knowledge and competence and to contribute to the generation of informative data regarding reuse in general (ENOVA, 2022). The protocol is separated in three:

Measure 1: Mapping of reusable components

The mapping should provide a foundation to make decisions regarding reuse and increase the volume of reused materials in the market. The owner receives support to perform investigations, mapping, and documentation for a report regarding reuse. Materials should be used internally or distributed through a marketplace.
Support from ENOVA can cover up to 50% of related costs to a total value of 200 000, - NOK.

Measure 2: Possibility study for reuse and area flexibility in buildings

A possibility study can shed light on alternative solutions in the early stages of a building project. ENOVA can provide support for one or several actions

- Buildings implementing reuse
- Design buildings for future disassembly and reuse
- Rehabilitation prioritized instead of new building
- Design with the flexibility of multiple areas of use

Support from ENOVA can cover up to 50 % of related costs to a total value of 300 000, - NOK.

Measure 3: Including reuse in the project planning

Reusing building components often leads to more work during the project design phase. ENOVA can cover the costs of the extra hours directly related to reuse in project planning. Such actions can be:

- Searching for reusable materials available
- Adjustments to technical or aesthetic design
- Planning of logistics
- Extra work related to documentation and product declaration
- Work related LCA and LCC of reusable materials

Support from ENOVA can cover up to 50% of related costs to a total value of 600 000, - NOK.

3.7. Materials

The material used in the structural system has a great impact on design, geometry, and the performance of a building. In recent years we have seen the evolution of a variety of hybrid materials, this means a combination between two or more material types. It has also been a significant growth in the use of ceramics, polymers, and other plastics, but these are mostly used for smaller components and are less relevant for structural design. In the building industry a material is identified and applied to serve a purpose often based on their mechanical properties, but sometimes also other aspects are governing (e.g., thermal, climatic, fire safety, exposure of moisture etc.) (Designing Buildings, 2021). In a reuse scenario it preferred to use materials and elements that are prone to accept bolted or other mechanical connections. Components that depend on monolithic connections* make disassembly difficult or even impossible without damaging the element beyond repair (DiBK, 2021).

> *Monolithic connection is a connection where a binder such as cement or glue is used to join two or more elements. The connection is very strong and provide fixity, but it is permanent, meaning that the connection must be destroyed to break the connectivity.

3.7.1. Steel

In the construction industry steel components are often made of structural steel, which is an alloy between iron and carbon. Structural steel can be of different qualities and the required properties are obtained by changing the ratio of these mentioned components. Carbon is very strong and stiff, while iron is more ductile. Steel is famously known to be a strong and durable material, at the same time it is ductile and moderately cost effective (The Norwegian Lexicon, 2021). By making modifications on the composition of the alloy, perform galvanization or other surface treatment, one can change the properties of the steel and for example remove the possibility of forming rust(corrosion), which is the deterioration of the steel (The Norwegian Lexicon, 2021). As for durability and material deuteration, steel is considered very long lasting and if treated correctly or used in a dry place steel can theoretically sustain its mechanical abilities for hundreds of years (Cooper, 2014). In structural design, steel is considered as *isotropic*, which means that the material has identical properties in all directions, making steel members very versatile (Matmatch, 2019).

According to current standards, it is normal to have 70% recycled steel in rolled H- and I-profiles while for example steel used in reinforced concrete can have a recycling grade of 100% (Bygg Og Bevar, 2019). Steel is therefore a material that has a high recycling value. Due to its good mechanical properties, steel as a material can be used to create strong but at the same time slender members, making it well suited for light structures, e.g., frames. Steel members are also very compliable with bolted connections, an attribute making steel structures possible to disassemble (figure 20) (DiBK, 2021). In structural design we are often worried about creep phenomena, but at room temperatures or below, creep is usually ignored in the case of steel. This means that if the steel components are kept below their yield strength during use, there will be no change in mechanical properties for future reuse (Girão Coelho, et al., 2020). The biggest challenge for the reuse of steel structural components is regulatory. Reports show that CE-certification is so time and resource consuming that it is not economically profitable to reuse compared to just recycling the steel members as scrap and buy new components (Girão Coelho, et al., 2020).

Figure 20 - Example of a bolted connection in a steel frame structure (VMC Structural, u.d.)

A study performed in Sweden showed that there are no juridical obstacles for reusing steel elements. If the steel member is standardized and can be documented with sufficient product declaration, then it can be reused. In cases with a lack of documentation the members can also be reused, if the members are tested, and proof of satisfying properties are documented (Husson & Lagerqvist., 2018). It should be mentioned that the Swedish legislation for distribution of used building products is not the same as the one used in Norway and does not have the same requirements for CE-certification or equally satisfying verification of products. Swedish governmental officials have concluded that CE-certification is not a sustainable option for verifying the applicability of used building components. The products should rather be certified based on Swedish building regulations and technical guidelines (DiBK, 2021).

3.7.2. Timber

Timber is a processed wood material and has many application areas, one being an important component in buildings and other structures (The Norwegian Lexicon, 2019). In addition to being a natural organic material, timber is also highly anisotropic, separating it selves greatly from many of the other construction materials. Anisotropic means that timber does not have the same properties in all directions (Matmatch, 2019). This is because timber as a material is composed of many individual fibers in the longitudinal direction of the height of the tree (figure 21). The mechanical properties of the grains/fibers and the relationship between them varies a lot depending on the direction which the grain is being loaded. In the longitudinal direction timber is strong because we are stretching or compressing each individual fiber, in the radial and tangential direction to the grain, timber is very weak due to low connectivity forces between the grains (Khelifa, 2014).

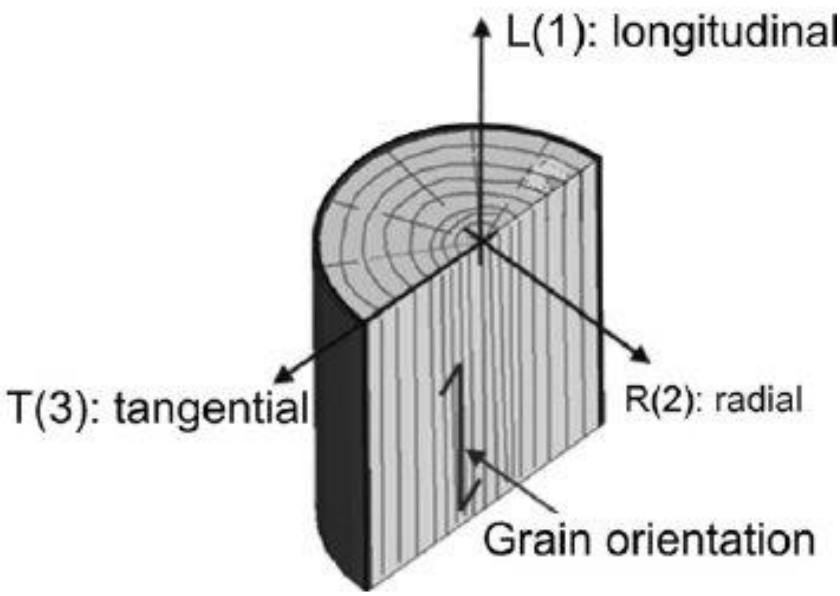

Figure 21 - Section showing the grain directions in timber (Khelifa, 2014).

Timber is not constricted into creating members coming straight from the wood log but can be processed to create a big variety of materials with different properties. For structural members we often observe types such as normal structural timber, GL (glulam), CLT (cross laminated timber) and LVL (laminated veneer lumber) (figure 22). Timber has the advantage of being lightweight compared to its strength. Since weight is an important factor for deconstruction it makes timber elements well suited for disassembly. As a structural system timber can be implemented in different ways, e.g., light-frame-construction, post and beam or massive timber construction (log construction and CLT) (M-ERA-NET, 2020). A quality all these systems have in common is that they are easy to shape and are compliable with mechanical connections e.g., bolts, screws, and wooden dowels (Futurebuilt, 2020). Wood is a natural resource in Norway and other neighboring countries, it is lightweight making it suited for transport, assembly, and disassembly, and is considered to have low carbon emissions (M-ERA-NET, 2020).

Figure 22 - From top left: GL, LVL, CLT (The international EPD system, u.d.).

If the timber element is in good condition without any sign of rot or other deuteration, experiences from the industry indicate that the strength is not significantly degraded. The property that potentially will change is the ductility. Timber loses ductility as a natural reaction to the aging process of the material. The strength, which is typically the dimensioning property of a structural component, has the tendency of *increasing* (Sørnes, et al., 2014). In cases with GL, CLT and LVL the situation is different. These products (e.g., a beam) consists of a layering of lamellas that are often connected with an adhesive but can also be connected mechanically. Along with the change of properties and potential deuteration of the wood over time, one must consider how the adhesive will react to aging. A Japanese study simulated the aging of GL products with different wood types and adhesives. In the aging treatments, the wood failure percentage of glulam did not decrease although the shear strength declined. It was assumed that the cause of decrease in shear strength was because of wood cracks rather than deterioration of adhesives (Okada, et al., 2019). In the production of GL, it is normal to have a lower material quality for the centered lamellas since these are less stressed (figure 23) (Johansson, Marie, 2016). Kilvær emphasizes that this method of production needs to be considered in a reuse scenario where the cross section might be modified. The change will result in an asymmetry in material quality in the cross section, and this means that the member will lose strength (Kilvær, et al., 2019).

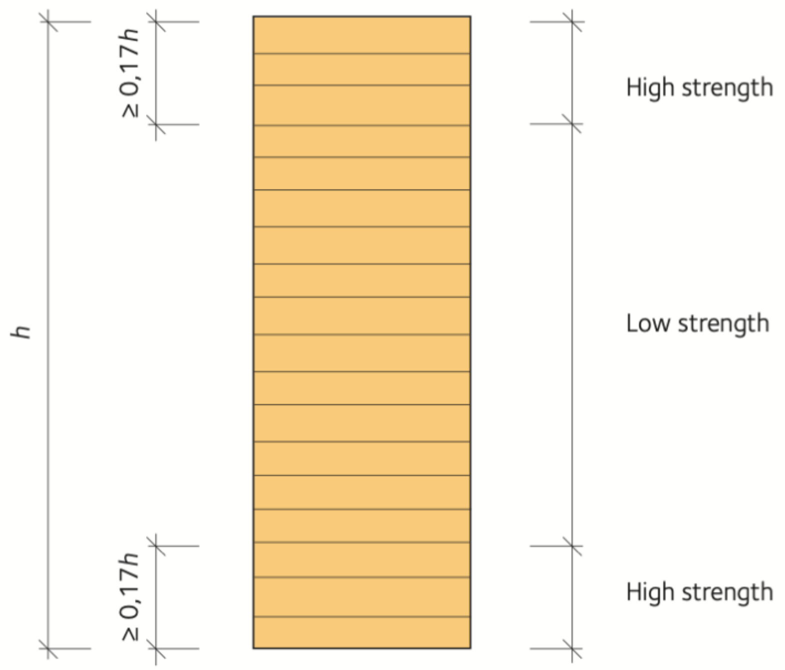

Figure 23 - GL beam showing different material quality for the lamellas depending on positioning (2016).

High stiffness related to mass give structural designers in some cases the freedom to over dimension elements if it is reasonable. This was done in the project Brummen Town Hall in the Netherlands (figure 24 & 25) (M-ERA-NET, 2020).

Figure 24 - Brummen Town Hall (Petra Applhof, RAU Architects)

Figure 25 - Dismountable timber beams and columns in Brummen Town Hall (courtesy of Petra Applhof, RAU Architects)

The elements have bolted connections, and the beams were 20% thicker than necessary to make them more appliable in potential reuse-projects in the future. The measures for increasing the reusability resulted in a structure where 90% of the materials can be dismantled and reused after an estimated service period of 20 years (Ellen MacArthur Foundation, u.d.).

3.7.3. Concrete

Concrete is a material created by mixing water, cement, and aggregates such as sand or gravel. A chemical reaction between cement and water starts a hardening process resulting in a solid and durable material known as concrete (The Norwegian Lexicon, 2019). Concrete alone has very good capacity when it comes to compression, but it is weak regarding tensional forces. This has led to a common practice of introducing steel as reinforcement, resulting in a material called reinforced concrete. The reinforcement can be bars, mesh/nets, fibers, or tensioned cables that can be tensioned either before or after the concrete has hardened. Production of reinforced concrete elements for construction projects can be done in two ways; one way is to cast the elements on site and the other way is to produce them industrially as a pre-cast element (figure 26) (The Norwegian Lexicon, 2019).

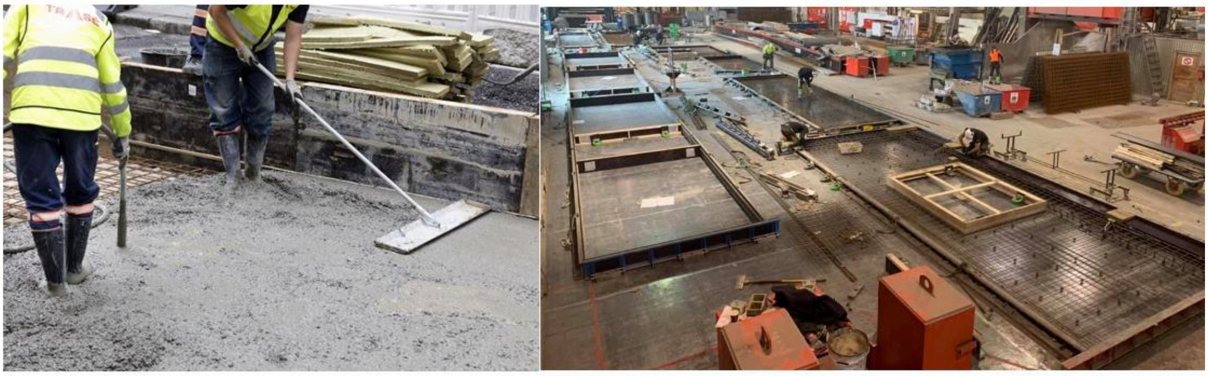

Figure 26 – On-site-casting (left) (Teknisk Ukeblad, 2018) and pre-cast (right) (Overhalla Betongbygg, 2020)

A big advantage of concrete is that it can be casted into many different shapes, making it very versatile. One way of using concrete is creating surface elements such as floor slabs. There are different types of slabs, but the most common is hollow core slabs and since the 1970´s a big quantity of large building in Norway has been built using these elements (figure 27). Tension capacity of reinforcement and compression capacity of concrete makes it a high performing construction material, where one of the major attributes being the ability to reach large spans. Traditionally concrete has been a building material connected with monolithic connections, creating problems in situations where disassembly and reuse is considered. Additionally, the elements have a big mass, making disassembly and transport energy consuming. This has led to a practice in the industry where obsolete concrete structures rather than being reused, have traditionally been recycled or worse, deposited as waste.

Figure 27 - Hollow core slabs (Contiga, 2019).

Concrete is recycled by crushing the material into stones and gravel and then use this as aggregates in new concrete or more commonly used as backfilling for building and infrastructure projects (Rakhshan , 2020). In a study performed by Brambilla it was documented through a comparative life cycle analysis that there is great potential in moving away from the traditional monolithic nature in the current shear connection practices (Brambilla, 2019). The report states that savings up to 80 kg CO2-eq/m^2 is realistic in addition to preventing the use of virgin resources. In cases where transportation distances are very long (1000+ km) between disassembly project, potential testing facility and final location, reuse is considered non-benefitable (Brambilla, 2019). As of today, reuse of concrete elements normally leads to increased time consumption compared to traditional demolition. Traditional demolition practice is executed swift and effective, but brutal, resulting in that the concrete cannot serve at any higher value than being used as aggregates or in backfilling (Kilvær, et al., 2019).

4. State of the art

4.1. BREEAM-NOR v.6.0

The national distributor of BREEAM in Norway, Green Building Alliance published on the 28th of February 2022 a new revised standard “BREEAM-NOR v.6.0”. Prior to the publishing the head of communication and marketing in Green Building Alliance stated:

“*The goal is always that the tool pulls the industry against better environmental quality in buildings. TEK (technical building regulations) is only a minimum. BREEAM is a method to make the industry perform even better up until 2050*” (Arkitektnytt, 2022).

Green Building Alliance acknowledged that the revision of BREEAM from 2016 had big voids regarding sustainable building practice, particularly regarding reuse and DfD. They also highlight the fact that the industry is going through a rapid and continuous development when it comes to topics related to sustainability and therefore repeated revisions is both expected and necessary.

BREEAM-NOR v.6.0 commits to follow the EU taxonomy (Norwegian Green Building Alliance, 2022), which is a classification system and one of the most important parts in the action plan for a sustainable economy that complies with the climate goals of the EU. The classification system sets out to define what is a sustainable activity and what is not, and in this way dictate the private capital in developing in a green direction (The European Commission, 2021). Even though the taxonomy is created to make an impact in the overall financial sector, it is expected to have great affection on many parts of the global marked, including the building and infrastructure industry (Norwegian finance department, 2021). By following the EU taxonomy, BREEAM-NOR oblige to follow some criteria to limit climate change:

- Taxonomy´s technical criteria for improvements to limit climate change (Technical Screening Criteria – TSC)
- Criteria to do minimum damage (Do No Significant Harm – DNSH)

The relevant criteria from these two categories are presented in Appendix II – Criteria based on the EU taxonomy.

With respect to the scope of this thesis, the remaining part of this section presents only the most impactful additions related reuse and DfD in the new BREEAM-NOR manual.

4.1.1. Criteria in BREEAM-NOR v.6.0 relevant for reuse and DfD

This section introduces criteria from the new manual that has been found relevant for the implementation and development of reuse and DfD in the building industry (Norwegian Green Building Alliance, 2022). BREEAM-NOR is as stated earlier, a manual that can be used voluntarily to achieve a certification and therefore no projects are legally obliged to follow any of these criteria.

Man 02 – Life cycles costs and life cycle planning (Norwegian Green Building Alliance, 2022, pp. 38-44)
Create value for the entire life cycle of buildings by using life cycle costs (LCC) to improve design, choice of products, maintenance, and management, and at the same time aim focus on profitability in sustainable buildings.

Mat 01 – Sustainable choice of material – LCA and climate gas calculations (2022, pp. 225-233)**.**
Recognize and encourage to the use of building materials with low environmental impact throughout the life cycle.

Mat 02 – Sustainable choices of products (Norwegian Green Building Alliance, 2022, pp. 233-242)**.**
Encourage that there should be robust and comparative data about the environmental impact of a building component in the product declarations, and at the same time recognize and encourage the use of building components with a low environmental impact throughout the total life cycle of the building.

- This criterium is focusing on the material composition and especially on hazardous substances. As a rule, the following guidelines are set regarding reuse:
  - Building components that are introduced as reuse (from owned buildings or been bought) should be met with the same criteria regarding documentation as if they were bought new from producer.
  - Building components that has not been moved, processed, or refurbished does not have to be declared and documented up against the minimum requirements in TEK17.

Mat 06 – Material efficiency and reuse (Norwegian Green Building Alliance, 2022, pp. 259-266)**.**
Promote reuse and optimize the use of new materials.

- In case of demolition work a mapping of reusable materials should be executed. Preferably carried out by a qualified person within a reasonable time before deconstruction or potentially demolition finds place. That is because this information is important for the planning of deconstruction activities. The following should be considered:
    - Magnitude and type of building component suitable for reuse.
    - Assessment of the remaining service life.
    - Evaluation of the criteria set for documentation and an assessment of this.
    - Simplified evaluation of the deconstruction and recommendations for reuse.

- Material efficiency
    - Use materials and components that can be reused or recycled after end-of-life.
    - Reuse building components or use materials with a high recycling value.
    - Implement design for deconstruction in project planning.

- Reuse of external components. At least 2 product groups on level 3 in NS 3451 (figure 28) are from reuse and it must be documented that at least 20% of the total mass of this product category is reuse (e.g., 20% of the total mass of all beams are reuse). The acquisition of these components should origin from outside the project.

- Satisfy FutureBuilt requirements, 2.3 Reuse of Building Components for Circular Buildings (Appendix III – FutureBuilt requirements)

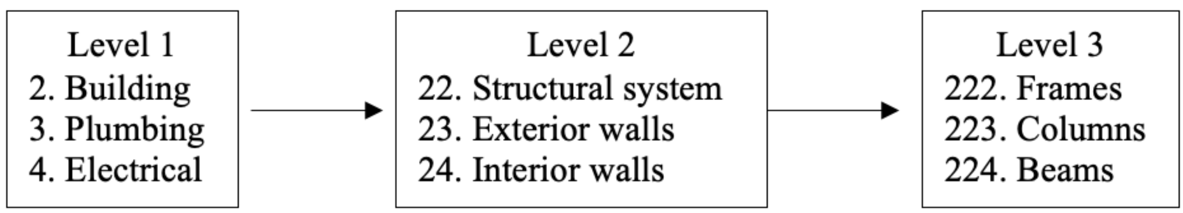

Figure 28 - Example of the level hierarchy for building components according to NS 3451

Mat 07 Adaptivity and reusability (Norwegian Green Building Alliance, 2022, pp. 266-273)**.** Avoid unnecessary use of materials, costs, and potential abandonment of future buildings, in addition to designing for reuse of building components and material recycling when the building is to be rehabilitated, deconstructed, or demolished.

- Mapping of resources should be done by a qualified person* with the task of defining a guide to give the project owner an overview in regard of maintenance, future reuse, and material recycling.

*A qualified person should have relevant experience related to the environmental aspect of building materials, reuse, recycling, or maintenance.

- Adaptivity and reusability: recommendations
  - It should be considered how adaptivity and reusability can be sustained
  - Based on this consideration it should be made recommendations that tries to facilitate or simplify processes for adaptivity and reusability.
- Adaptivity and reusability: implementations
  - The recommendations stated should be updated relative to the potential new and accessible information.
  - The final solutions should be justified and possible deviations from the original recommendations must be reasoned for.

Wst 01 – Waste management on the construction site (Norwegian Green Building Alliance, 2022, pp. 274-281)**.**

Develop a waste management plan to process waste from construction, demolition, and excavation. The amount of waste should be reduced to a minimum while reuse and recycling must be a priority.

- A certain percentage of the waste-mass generated should be distributed in separate categories of waste and preferably prepared for reuse (table 8). As the minimum criterium there is no demand to prepare a defined share for reuse, only that the waste is separated based on waste type.

Table 8 - Reward scheme for waste management

Points	Share sorted based on waste type	Share prepared for reuse OR recycling
Minimum criterium. No points	75 %	-
1	85 %	50 %
2	90 %	70 %

4.2. NS 3682:2022 – Hollow core slabs for reuse

Until recently there have been limited documents and standards on how one should proceed to test and verify a specific building component for reuse. Important figures in the Norwegian concrete industry have expressed opinions that the testing criteria is mostly based on new production and virgin elements. This makes the criteria unsuitable for validating components in reuse scenarios. The need of standardized methods has now led to the first document of its kind in this category. Standard Norway published on the 18th of February 2022 the document: **NS 3682:2022 – Hollow core slabs for reuse**. It is a standard that describes in detail the evaluation necessary to reuse an existing hollow core slab. The standard is based on NS-EN 1168 which describes the industrial production of *new* hollow core slabs.

NS3682:2022 presents a system that satisfies the requirements defined by TEK17 and DOK regarding the reuse of a product not certified by any harmonized standard. This has opened new doors for reuse in the concrete industry. The document contains criteria and guidelines for planning, deconstruction, preparing, testing, assessment, and documentation of reused hollow core slabs. (Norwegian standard, 2022). NS 3682:2022 have already proved to be useful and have been decisive in the process of reusing hollow core slabs for a project in Oslo (Kindem Tyholt, 2021) and in the reuse of long span concrete beams in Namsos. The following sections will present the findings from the standard considered to be the most impactful when it comes to reuse and DfD.

4.2.1. Procedure to reuse a hollow core slab based on NS3682:2022

Planning, deconstruction, and processing

- Planning must be done ahead of the deconstruction process; this includes collecting important data and documentation such as
    - Original production drawings, production plans, assembly schemes
    - MOM (management operation and maintenance data)
    - Other important technical or geometrical data available
    - All slabs must be assessed individually and given an identification

- Deconstruction should be considered as a reversed assembly process where the same precautions must be taken
    - Performed in a safe way with certified equipment
    - All extracted slabs must be tagged with their provided ID
- Processing after deconstruction
    - Potential top cast layers or casted element connections must be removed
    - Shape eventual angled ends and refill holes

Testing

Testing should be performed in a standardized way and the result of this testing is sufficient documentation to work as a declaration to reuse the product. The testing procedure includes:

- Carbonization depth
- Chloride content
- Alkali reactivity
- Compressive strength of concrete

- Hollow core slab tested to failure

Hollow core slabs assumed to be of the same type can be considered to origin from the same production series if:

- The hollow core slabs are from the same part of the building or the same project construction period, or
- The hollow core slabs are delivered from the same producer and factory and is produced within a period of six months.

The standard provides a table (table 9) presenting the testing rates of each the properties listed above.

Table 9 - Minimum testing requirements for a hollow core slab based on NS3682:2022

Property	Minimum frequency of test slabs	Minimum number samples
Geometry	1/1	
Weight	1/1	
Visual control	1/1	
Full scale testing	1/50	3[b]
Compressive strength (core samples)	1/20	8[c]
Compressive strength (rebound hammer)	1/5	3
Carbonatization depth[a]	1/20	10
Chloride content[a,d]	1/50	3
Alkali reactivity[a,e]	1/50	3
a - Visual inspection can replace testing where exposure class is declared to be X0		
b - Minimum number of samples assumes that the capacity from results is not lower than calculated value. Deviations from this demand documentation for cause and consequence		
c - Should be completed a minimum of 4 samples from two elements		
d - If it can be proved that the slab has not been exposed to chloride content the test can be neglected		
e - If it can be proved that the slab is produced in 2007 or later the test can be neglected		

The standard further presents how each property control should be performed. After tests are completed, properties of the hollow core slabs are listed in a declaration table (table 10).

Table 10 - Checklist for declaring a hollow core slab

Property	Unit
Width	mm
Length	mm
Thickness	mm
Weight	kg/m2
Compressive strength	Class
Characteristic moment capacity	kN/m
Exposure class	Class
Absence of hazardous substances	Confirmation
Fire resistance	Class
Excecuting contractor	[name]
Date of verification	date
Controlling party	[name]

NS3682:2022 based on NS-EN 1168, will by this provide sufficient documentation and declaration so that hollow core slabs can be reused.

4.3. Material passports and urban mining

In the last decades the progress of digital technology has highly affected the how the planning, designing, and building of a structure is performed. After BIM became a standard tool for any modern building project, the way of processing, exchanging, and storing information has evolved into something very different from traditional 2D drawings and e-mail correspondence. The rapid development and progress of BIM have allowed the industry to search for new methods to take advantage of the digital revolution (Honic, et al., 2019).

Material passports and BAMB (buildings as material banks) have in the last years proven to be focus areas related to CE in the building industry (figure 29 & 30). BAMB was introduced as an innovation action in the EU funded Horizon 2020 Program and takes aim to be a systemic shift where dynamically and flexibly designed buildings can be incorporated into a circular economy. The goal is that the urban landscape of buildings will function as banks of valuable materials – slowing down the usage of resources to a rate that meets the capacity of the planet

(BAMB, 2020). To achieve this milestone, one must compile both qualitative and quantitative data about the embedded materials in both existing and new buildings. Material passports (MP) will be an important tool in obtaining success in this urban mining process.

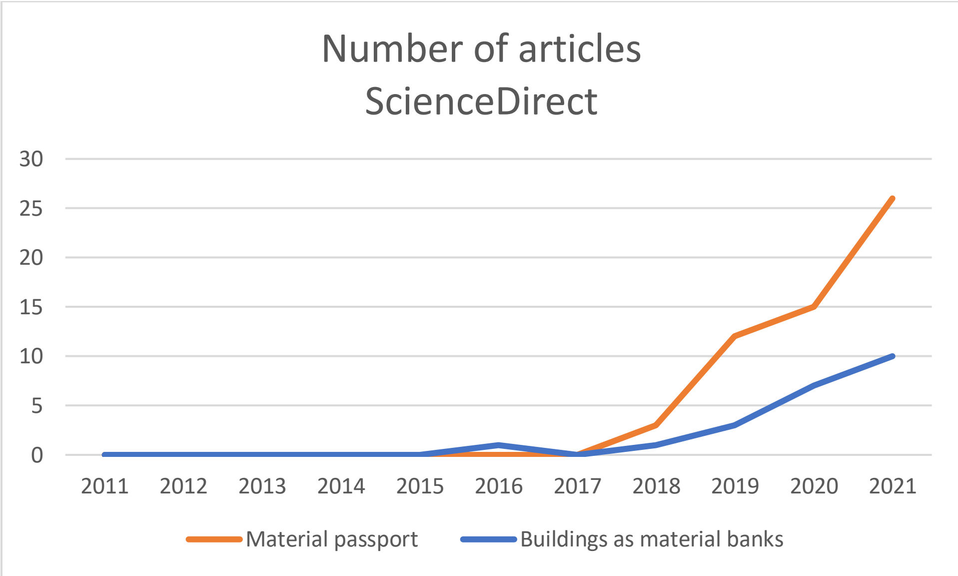

Figure 29 - Development in the number of scientific papers on ScienceDirect related to the subject

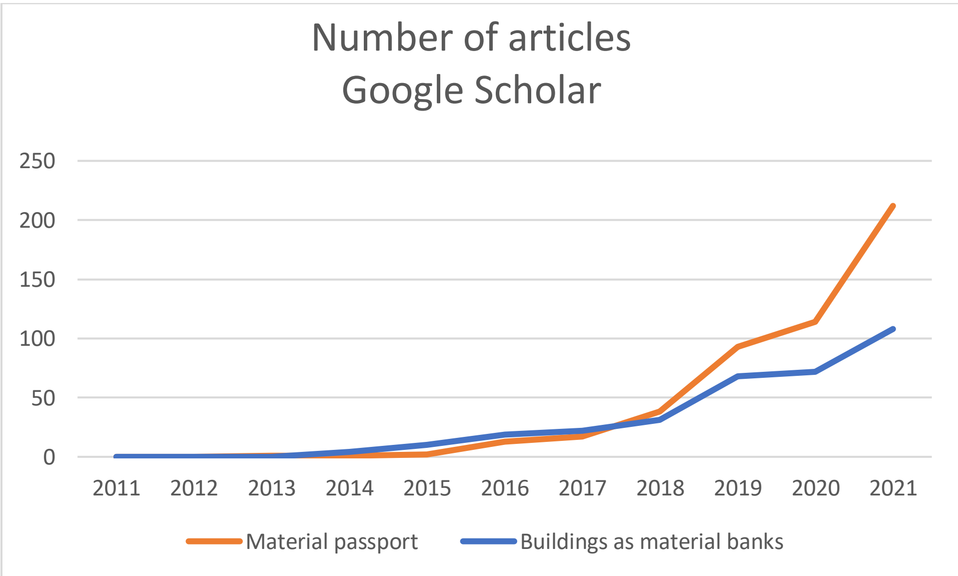

Figure 30 - Development in the number of scientific papers on Google Scholar related to the subject

4.3.1. Material Passport what is it?

Material passport (MP) is as a design-optimization and inventory tool for buildings. The MP display materials in a building and by viewing the passport one can evaluate the material´s both geometrical and mechanical properties, reuse and recycling potential, and environmental impact. In addition to this the MP serves as a support tool in early design stages to evaluate and optimize the reuse and recycle potential and ecological impact of a component in a building (Honic, et al., 2021). Madaster is a platform with an online library of materials that exists in the built environment and has the mission to reduce waste by providing materials with an identity. Madaster defines MP as

"*A digital document that records the identity of all construction materials used in a building*" (Madaster, 2021). According to EU´s Horizon 2020 program a MP is

"*An electronic set of data describing defined characteristics of materials in a product that gives them value for recovery or reuse*" (BAMB, 2019).

By studying the figures 29 and 30 one can see the growing awareness of MP and buildings as material banks the recent years. Correlating to the trend of CE; where the number of articles related to CE in the building sector has had an average annual increase of 21% since 2005 (Norouzi, 2021).

4.3.2. How to create a MP

For buildings being designed and built today, all the desired information related to the materials is available, making the implementation of MP is easy. Most building projects of considerable size in Norway use BIM and they have EPD´s for almost every material used in the project. By using the qualitative data from the EPD and BIM, most of the information needed for a MP is already in place (figure 31). By merging this data together and include information about separability and connectivity, the MP is complete (Honic, et al., 2019)

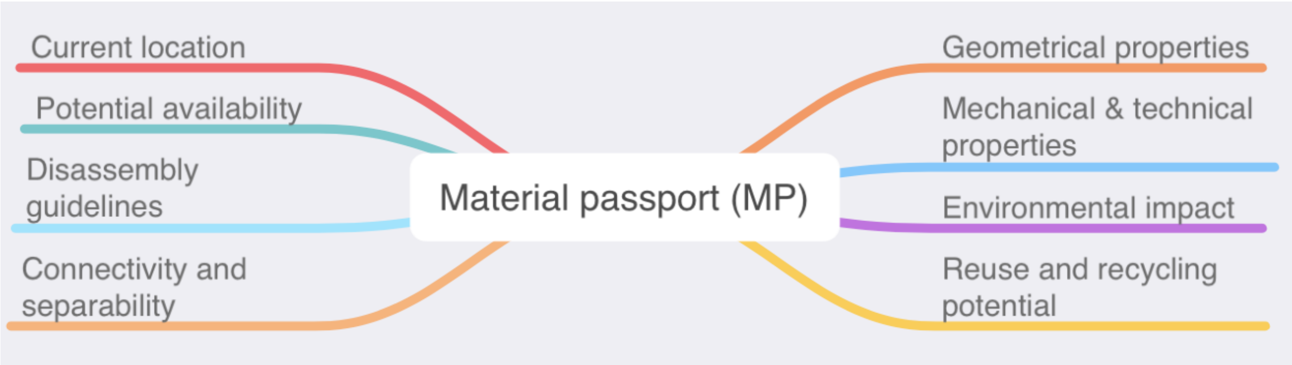

Figure 31 - Illustration of the data contained in a material passport (MP)

For already existing buildings it is often a challenge to collect the necessary information to create a MP, mostly because a lack of documentation. The magnitude of this challenge increases relative to the age of the building. Traditionally and up until now, the method used has been *ad-hoc*, meaning that the building components have been treated spontaneously and considered as either renewable or waste as-we-go during the demolition.

Honic states that one can use modern laser scanning techniques to create a point cloud, which essentially is an enormous amount of tiny individual points plotted in a 3D space (Honic, et al., 2021). This point cloud can be used to create an accurate geometrical replica of a building (Geoslam, 2020). The laser scanning method is highly effective when it comes to geometry but gives little information about the material properties of the scanned object. Therefore, a visual or physical investigation is often necessary to supplement the laser scan technique. To make more accurate measurements, it is currently performed extensive research using GPR (ground penetrating radar). A technique that can define both quantitative and qualitative data of embedded materials in buildings (Honic, et al., 2021). GPR is based on sending high-frequency electromagnetic waves (typically several MHz up to a few GHz) into a material and record the strength and the time required for the return of any reflected signal. This can identify material type and thickness of an element without the need to physically penetrate the material(s) (Norwegian Geotechnical Institution, 2021). Based on these techniques designers can create accurate digital twins of already existing buildings, allowing for the implementations of MPs, long before a building is to be renovated, de-constructed or demolished (Honic, et al., 2021).

4.3.3. How to use a MP?

MP can be used to map existing individual building elements and consider their value until the end of their life cycle. Material passports increase the amount of useful information related to a building element and will bring more confidence in reclaimed products. The possibility to include disassembly instructions in MP will be beneficial in the practice of non-destructive deconstruction (Fivet & Brütting, 2020). This information simplifies processes related to DfD, reuse, and waste management in demolition projects.

If material passports continue the development and becomes a standard implementation in building projects, they will secure an overview of the existing building stock in the urban landscape. Companies working with disassembly and demolition can access BIM models integrated with MPs and through this supply the marked with valuable resources. Through digital marketplaces such as Madaster or Rehub (a Norwegian version of Madaster), other contractors and builders can buy and reuse elements and are by this closing the material loop (Rehub, 2021). MP can allow builders to know what exists on site or nearby locations before starting any new project, opening the opportunity to extract reusable materials before placing orders for new production based on raw materials (Charef & Emmitt, 2020).

Once MPs exist in all buildings the digital building stock for urban areas will be very big and provide builders with a large variety of elements. Researchers believe that if the market for reusable elements becomes economically beneficial and the stock of existing elements big enough, the industry might experience a shift in how projects are planned and designed. They predict a practice where not only the area of use and aesthetics dictate the design, but equally impactful is the stock of reusable materials available at the time of construction. A potential technique to implement this philosophy is stock design.

4.4. Stock design – Future design practice?

4.4.1. What is stock design

In previous projects where minimalization of the environmental impact has been a center of attention, the job of a structural engineer has been to develop a system optimized against material quantities (low mass) and the use of low-impact materials. Currently, still at its infancy, it is (re)emerging another strategy: the reuse of structural components over multiple service lives and in new geometrical compositions (Fivet & Brütting, 2020). This circular economy strategy is a contradiction to the common practice in structural design where the components are manufactured *after* the preliminary design of a building. By using this new approach, the design of the structural system will be synthesized from a stock of already existing components. This technique is commonly getting known as *stock design*. The idea of stock design is that a form finding program will use structural optimization formulas to design a system from an available stock of elements.

4.4.2. How does stock design work?

Stock design is a reversed way of designing compared to traditional design. In stock design it is the available stock of elements that dictate the structural geometry. Generally, structural optimization is carried out using continuous design variables to optimize against for example weight by using cross section areas or element length. This method is not practical in case of reuse based on a limited stock of elements (integer). Instead, one should introduce some constraints (e.g., a set of elements with a limited number of lengths and cross sections), thus making the design variables discrete (Brütting, et al., 2018).

Formulations from Brütting et. al. has shown how layout optimization and stock utilization are defined as MILPs (mixed integer linear problem) and can be solved to global optimality through acknowledged algorithms such as branch-and-bound methods (Brütting, et al., 2020). The availability of proven global optima allows for a precise benchmarking between reuse versus new construction solutions in regard of potential environmental and economic benefits.

A case study presented by Brütting shows how these methods can be used in a scenario where a great number of electric pylons have served their purpose and is to be removed. The use of bolted connections and the fact that the assemblies are a repeating structure, the pylons cumulate into a large stock of elements. These can be evaluated for a new purpose using structural optimization techniques. In this case study the elements were mapped and sorted in categories based on crossection and length. The product of this study was a design used as a contribution to the redesign of Lausanne´s train station in Switzerland that was under planning at the time (figure 32) (Brütting, et al., 2019).

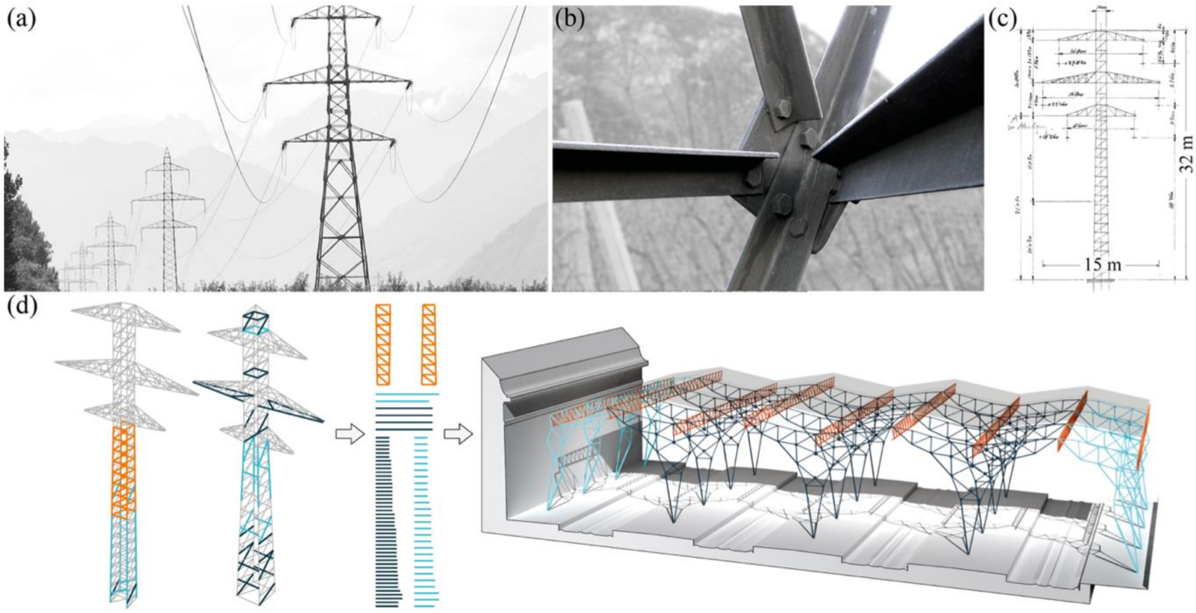

Figure 32 - Case study Lausanne Train Station roof: (a) typical power line and electric pylons, (b) connection detail at a pylon corner, (c) archive plan of an electric pylon and (d) roof design strategy and concept (Brütting, et al., 2019).

The rehabilitation project was under pressure in regard of both time and economy, so the solution with reusing the pylons was deprioritized (Brütting, et al., 2019).

4.4.3. Benefits and challenges with stock design

The presented case study resulted in a conclusion that the proposed optimization method produces structures that satisfies valid design criteria (ULS and SLS) in realistic scenarios. The study also revealed that structures from stock design are often over-dimensioned in regard of mass, but despite of this delivers solutions that have a lower GWP than new weight optimized solutions. It is highlighted that this was a singular case study with social and geographical dependencies and therefore the data is not representative for all scenarios. The report mentioned that this case is sensitive to unknown variables such as emissions related to selective deconstruction, transport distances, and the fact that reuse structures often are over dimensioned (Brütting, et al., 2019). All these factors should be considered for potential reuse projects in the future.

In a case study by De Wolf et. al. (2018) to evaluate the potential environmental benefit of using stock design to reuse structural components, the main structure of a fictional steel baseline building is compared to a structure based on stock design. The proposed building is a steel frame with steel columns and a grid of secondary steel beams supporting prefabricated concrete slab elements (De Wolf, et al., 2018). Based on the existing literature the study chose to see how three uncertainties related to stock design and reuse can affect the embodied carbon emissions of a reuse project. The three uncertainties were measured in ECC (embodied carbon coefficients) and was categorized as: over dimensioning, transport distance and ECC related to selective deconstruction.

Results showed that in cases with 25% over dimensioning and a transport distance of 300km the potential savings could be up to 20% compared to the baseline building. The study singled out that quantifying a value for the emissions related to selective deconstruction was difficult, since this practice is still very uncommon. Figure 33 shows graphs that present the influence of transport distances and ECC of selective deconstruction, respectfully, related to carbon emissions of the total load bearing system in the reuse case. Figures also showing the influence of oversizing the structural elements.

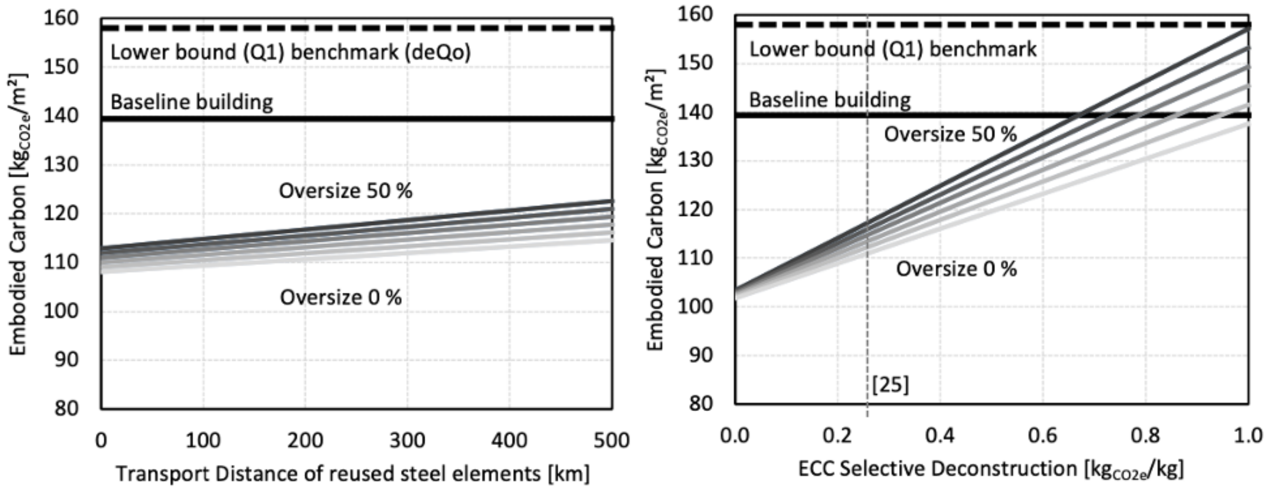

Figure 33 - Embodied carbon of benchmarked lower bound, baseline and reuse design cases for: varying transport distances and oversize percentages (left) and varying selective deconstruction values and oversize percentages (right) (De Wolf, et al., 2018).

In this study the transport distances needed to be over 2000km to exceed the baseline building (De Wolf, et al., 2018).

5. Case studies

5.1. Økern Bad – Design for deconstruction

There is currently an ongoing renovation of Tøyenbadet in Oslo, this has led to a lack of swimming-pool facilities in the area. In order to solve this problem, the department of culture and sports in Oslo challenged the industry to provide solution for a temporary facility (Nuno Architects, 2020). Nuno Architectures AS created the project known as Økern Bad. The structure is the only special facility in Norway with the intention of disassembly and re-erection at a different location and once Tøyenbadet is available to the public again the first relocation will take place. The design goal is that the structure can be constructed, dismantled, and re-constructed 5 times over a period of 15 years. The facility is made up of two systems, the main volume is a cathedral-structure housing the pool and the second volume is wardrobes and reception built up by container modules (figure 34 & 35).

Figure 34 – Cathedral structure and container modules in the background (photo credit: Tove Lauluten, Oslo KF)

Figure 35 - Cathedral structure (photo credit: Tove Lauluten, Oslo KF)

The primary structure consists of GL-arches creating a maximum height of 10 meters, the secondary structure is horizontal GL-beams, and it is cross-bracing of steel rods. All these components are, when possible, joined with bolted connections making it fit for deconstruction (figure 36).

Figure 36 - Illustration showing bolted connections in the structure (photo credit: Tove Lauluten, Oslo KF)

The exterior is a custom-made PVC coating with insulation that can be detached and reused along with the other building components. Welded steel plates make up the volume of the pool, these can be cut and re-welded on the new site. The foundations are produced in low-carbon concrete class A and are not permanently fastened to the ground, making them a movable part of the building mass (NTB, 2021). The project committee were also obliged to present a detailed plan on how deconstruction, in-between-site-transport, and re-construction were to be performed. The result was a plan where everything could be deconstructed with mobile crane and no need of special transport to the next site (OsloBygg KF, 2021).

After the first erection of Økern Bad the building council in Oslo is reckoning this to be a revolution within green city development. Head of commerciality and development in Oslo, stated after the facilities were opened:

"*Økern Bad sets a new standard for the planning and designing of temporary structures. From here on out we will define clear demands and guidelines for deconstruction and reuse for all our future temporary buildings so that the environmental impact is minimalized*" (NTB, 2021).

5.2. Upstream reuse project based on NS 3682:2022. Namsos, Norway.

In 2021 it was concluded that a large industrial building in Namsos, Norway was obsolete and should be demolished (Namdalsavisa, 2021) (figure 37). The city council hired a local structural consulting company to evaluate if some components were reusable for projects in the future. Conclusion of the investigation was that several long span beams were reusable and could be disassembled from the existing structure. The consulting company were also included in the planning of a new industrial building close by, and therefore suggested this as a new location for the concrete beams. Due to no change in ownership, it is not a commercial distribution of products, releasing them of documenting on the same level as CE-certification (DiBK, 2016).

Figure 37 - Obsolete industrial building in Namsos, Norway. Photo credit: Bjørn Tore Ness

The testing and certification of beams and roof-elements (figure 38) were done by following the procedure of NS 3682:2022 as explained in chapter 4.2.1. Material samples and some whole elements were transported to laboratories and full-scale testing spaces in Trondheim. At these facilities the investigations and documentation work were performed by SINTEF. Because this project is currently ongoing, the available test results and LCA data is limited. The laboratory results concluded the properties had experienced minimal changes, proving that the elements had a service lifetime more than adequate for new projects.

Figure 38 - Concrete beams (left) and ST-elements (right) extracted from demolition project in Namsos. Photo credit: Jon Aunet (author)

Conversations with experts involved in this project pointed out that the climatic benefits of reuse are substantial, and they used a comparison with new element production to prove this. The preliminary calculations suggest that reusing the extracted concrete elements produce under a fifth of the global warming potential compared to virgin production. This is a substantial reduction, but preliminary data should be considered with a degree of uncertainty and more detailed calculations should be performed before concluding with a final result.

6. Discussion

6.1. Motivation, need and the potential of reuse and design for deconstruction

It is consensus among government, research community and construction business that the building industry needs to shift over to a circular economy. Based on literary research, legislations, regulations, and conversations with people in the industry there are indications that reuse and DfD are likely to play a decisive role in the transformation into a CE. The building industry is a major consumer of virgin materials and energy (40% of global energy consumption) and represents a large share of GHG emissions (25% of global carbon emissions) (International Energy Agency, 2019). Limitations to raw materials, population growth and urbanization will create more pressure in the built environment. A consequence of this pressure is that a building might be forced to adapt to a different use than first intended. Studies shows that social influences often lead to functional obsolescence prior to the end of service lifetime, resulting in premature demolition. Design for deconstruction and reuse could in these scenarios keep products within the material loop, prevent production of CDW and avoid extraction of virgin material.

Statistics indicate that Norway is a pioneer in recycling CDW in new projects, but in rehabilitation projects the current state is different. Waste from demolition activities is increasing a lot, suggesting a void in the demolition waste management. Findings show that almost half of the CDW generated in Norway origin from demolition. The building industry in Norway had a reuse and recycling percentage of 46% in 2019, which is not satisfying the goal of 70% defined in the EU taxonomy (Statistics Norway, 2021). The government should investigate the reasoning behind the insufficient results and make considerations on how the goal can be reached. Considering the waste hierarchy, the CE definition, and the fact that recycling often leads to a downgrading of the material value, one can determine that recycling is not the best option. All these reasons lead to the conclusion that reuse should be prioritized.

There are modern examples of both upstream and downstream reuse (DfD) such as KA13 and Økern Bad respectfully. Despite of these cases, the practice is still uncommon in the building industry. Studies have revealed that barriers such as high cost, lack of experience and regulatory demands related to testing and certification of products are retaining reuse from gaining momentum.

Initiatives from the industry (BREEAM, innovative projects), government (EU, national strategies) and academy (research and case studies) are actioned to make reuse and DfD a part of the circular economy in the building industry. An example of these initiatives are the chapters Mat 06 and Mat 07 in the new BREEAM NOR v.6.0 manual (chapter 4.1.1). These allow for a project to be rewarded for satisfying a set of criteria. On the other side, the government and other official guidelines are serving barriers limiting the progress of reuse. Most mentionable are TEK17 (§2 & §3) and DOK (§10) regarding declaration of building products. These documents have strict policies, making it expensive and time-consuming to reuse structural elements. One such example is the criteria for CE-certification to reuse building products (Appendix I – Norwegian legislations for the building industry). The regulatory challenges and weak incentives have a negative effect, making reuse challenging and non-beneficial.

The process of CE certification is based on the verification of *new* products, meaning that the demands for CE certified building components is less appliable to *used* components. A possible consequence is that distributors of reusable products are met with comprehensive and at times inappropriate demands regarding product declaration. Most structural elements are being designed with a service life of 60-120 years. Based on the demolition rates, there are indications that the lifetime of structural components often outlives the performance lifetime of a building. Considering that the mechanical properties often endure past the element´s service lifetime, this is indicating that a component could be used for several life cycles and strengthens the reason to reuse and implement DfD.

Based on the case study Økern Bad and the example of KA13, one can consider that both the willingness and the competence to implement DfD and upstream reuse are prominent. Despite of this, these projects are exceptions from the common practice and the potential of DfD and reuse is being restrained by regulatory demands. If Økern Bad is relocated within the city and Oslo Municipality remain as the owner, there is no change in ownership and no distribution of products, thereby removing the criteria set by DOK for CE-certification. This proves that reuse is easier when there is no demand for CE-certification and the current legislations could be interpreted as barrier.

Reviews of the literature have shown that the limited standardization for testing and validating building products creates a big uncertainty regarding responsibility, leading to a reduced confidence in the practice of reuse. By introducing standards to certify components for reuse, it will be easier to distribute and sell used building products. This could lead to an economic foundation that argues for an industry that promotes selective deconstruction. Consequently, this motivates designers to implement design for deconstruction principles and will serve a great impact when it comes to reducing waste and the related emissions.

NS 3682:2022 became the first document with a standardized method for testing and certifying a used structural element, resulting in a sufficient declaration equal to CE certification. This means that hollow core slabs tested according to this standard can be distributed as if it was a new CE certified product. Already showing great potential, the standard has resulted in the reuse of hollow core slabs in a project in Oslo and supported the reuse of concrete beams in Namsos. Experiences from the experts involved making the new standard are that the process was less complicated than first estimated. This indicates that developing more standards is easily achievable. NS 3682:2022 will reduce the risk and increase the confidence of builders and owners when it comes to the reuse of hollow core slabs.

Reports reviewed for this thesis have described that CE-certification of used steel elements is so resource demanding that it is not economically profitable compared recycling the members as scrap (De Wolf, 2019). Studies also indicate that the reuse potential of steel is better than concrete, highlighting the need for standardized testing methods to reuse steel components. The findings from Rakhshan indicate that one of the biggest obstacles for the reuse of steel was the lack of standardized methods for verification and declaration (Rakhshan , 2020). NS 3682: 2022 will therefore be a great contribution in solving the aforementioned challenge. Knowledge and experiences should be shared between the industries so that testing and certification standards for steel and timber can be developed.

The current low supply and demand for reusable components is keeping the distribution of reuse products to gain a solid footing in the market of building products. If these elements become more attractive, an economically sustainable marketplace will be achievable, and the construction industry can benefit from implementing DfD principles in their projects. Experiences from reviewed reuse projects show that applying selective deconstruction is challenging and often expensive in existing buildings. Monolithic connections, welds, adhesives, and inseparable materials are making deconstruction time and energy consuming. Consequently, it can be stated that in DfD design it will be important to avoid these building methods and prioritize techniques that improve separability. One such example is using accessible mechanical connections. Design for deconstruction guidelines from both official and private sector are now being provided so that planners and designers can reduce waste and minimize the downgrade of materials.

BREEAM-NOR v.6.0 Manual was along NS 3682:2022 published in February 2022. Due to attention placed on national sustainability goals the BREEAM certification has become very popular in the building sector, and it is considered as a lucrative stamp by the owners. Because of this importance, the manual can serve as a market regulator with the ability to influence the building sector in Norway towards BREEAMs desired direction. The new manual presents updated criteria that are directly related to reuse and DfD, such as mapping of reusable materials prior to demolition, implementation of DfD in project planning and reusing components obtained externally. By achieving these criteria, a project can be credited points, therefore motivating designers and planners to introduce reuse and DfD principles in their projects.

Up to date there has been a limited availability of specific guidelines regarding reuse and there is a gap in the official regulations regarding incentives related to reuse. In the building industry, profit is an important factor, making economic results one of the key motivations in many projects. Therefore, economic incentives would most likely benefit the implementation of reuse and DfD in the construction industry. In Norway´s National Strategy for a green and circular economy it is admitted that there are too weak incentives related to sale and redistribution of used materials. This is creating barriers through low prices, logistics related to storing the materials, marketing, and sales (Norwgian Government, 2021). The current strategy suggests several actions to reduce waste and increase reuse. The problem is that these actions circulate mostly around excess materials and demolition waste. It is not mentioned in the guidelines how whole and intact structural members should be reused. The only documents improving the rate of reuse of such elements has been provided by the concrete industry through the new standard NS 3682:2022. Possible reasons for this void in the guidelines could be a limited awareness from the state regarding the possibility to make structural members reusable or it can originate from a limited investigation of this influential part of the building mass. During the finalization of this study, ENOVA presented their first actions to provide financial support regarding reuse of building materials. These incentives are believed to have a positive effect of the practice of reuse and considered as an important contributor in establishing a sustainable reuse marketplace.

Limited capacity for temporary storage before testing and/or re-erection has recently been discovered as an unexpected drawback in the reuse practice and transition to a circular economy in the building industry. As explained in chapter 3.1.4, the industry has in the last 30 years adapted to a LEAN production and distribution philosophy. The consequence of this has been an effective flow of materials but also a drastic reduction in the need for storage capacity. This is in direct conflict with reuse and DfD, methods where storage is of fundamental importance. LEAN being counterintuitive in regard of reuse and design for deconstruction is problematic because the industry will need time to adapt to the turn-around in production philosophy. A solution might be that big distributors of materials in Norway establish separate branches that attempt to bridge the gap between LEAN production and reuse.

6.2. Quantifying the reuse potential

As part of sustainable building, it has become a standard procedure to perform LCA and LCC analyses on any project of a considerable size. To make DfD principles attractive a possible option is to reward the implementation of these principles in the life cycle analyses. How this should be done is under discussion. In case studies where researchers have tried to implement the reuse potential it has proven difficult to quantify the benefits of several life cycles and at the same time take into account the many uncertainties of the future reuse. To consider more than one life cycle, one must evaluate several steps of the circular process. These steps are illustrated in figure 39.

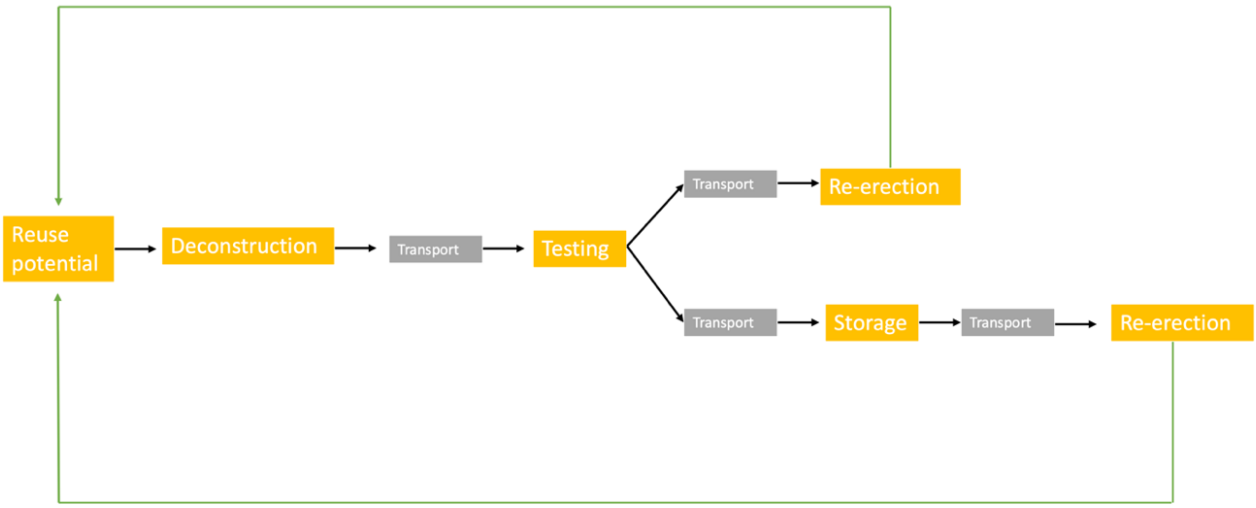

Figure 39 - Important aspects in a reuse scenario

The impact of the different processes is related to the material mass of the system, and it is therefore important to identify the quantities that are from reuse, recycling, and new production. Another important aspect is to consider the recycling value (yield factor, Y) of the material. A thorough investigation of the existing literature has revealed that there are big differences regarding this value depending on the material type. Based on the findings in this thesis, it is considered easier to quantify the GWP of several life cycles in the case of steel than it is for timber and concrete. The two latter materials experience a bigger reduction of value of utilization compared to steel during recycling. The reduction of material quality should also be considered, this is done by using the quality factors (Q_{RM} and Q_{VM}) introduced in formula 3.

This means that with recycling we are not fully complying to the fundamental principle in the definition of CE:

"(...) keep products, components, and materials at their highest utility and value at all times (...)".

Rakhshan, Kilvær and Gebremariam are stating that the reuse of concrete up to today has been backfilling operations and by this not utilizing the full potential of the material (Rakhshan, et al., 2021) (Kilvær, et al., 2019) (Gebremariam, 2020). Additionally, the reuse of large timber elements attracts more uncertainty because of the organic composition of the material and the deuteration of some of the biproducts, such adhesives used in GL and CLT. Due to the fact that GL, CLT and mass timber constructions are relatively new, there is also a gap in the existing knowledge when it comes to how aging and fatigue affect adhesives and the products in general.

Timber makes up for 30-40% of the total waste produced during demolition and new building projects in Norway (Hoennige, 2018). Most of this waste is burned in furnaces for obtaining energy. Based on their negative carbon dioxide contribution during photosynthesis, timber yield no emissions after combustion. Considering this fact, it may be argued that that the energy retrieved from burning recycled wood products has a socioeconomical value that can compete with the benefit of product reuse. In an environmental perspective, timber serve a great impact during growth. That is because trees store carbon within itself during the entire lifetime through photosynthesis and therefore collect large amounts of GHG emissions. By burning the timber, stored CO2 is released back into the atmosphere. Therefore, one can argue that the CO2 rather should be stored, e.g., in a wood product in a building. The reuse and recycling potential of timber should therefore be investigated more thoroughly in future research.

The numerical example in chapter 3.5.1 provided by the steel industry suggested that 30 out of 100 tons of steel can be reused after end of life, resulting in a global warming potential (GWP) reduction of 25%. In the presented project KA13, 70% of the steel sections came from local or external reuse. If a comparison is done between the share of reused steel section from the numerical example and the amount of reused steel in project KA13, there are indications that the amount of reuse in the numerical example is not ambitious enough. This suggests that reuse of steel components can obtain even greater GWP savings than the results from the numerical example.

6.3. Material Passports

Material passports can easily be implemented in new projects with the help of EPDs and BIM. In existing buildings, the process creating a MP is more laborious. That is because of the limited documentation for geometrical and technical properties of the materials. Creating MPs and developing deconstruction strategies are time-consuming compared to traditional rehabilitation and demolition planning. This suggests that the need for a reuse marketplace or sufficient incentives is fundamental to make the practice of material passports attractive.

Material passports will boost the productivity of material hubs such as Madaster and Rehub, and as the market for reuse gains footing these hubs will have the opportunity to grow. A potential problem is that too many of these hubs gets founded and starts operating individually with closed books. This will create a limited and disoriented market, reducing the selection for the buyers which further will affect the demand in a negative way. Rehub (Rambøll) and AV Ombruk (Asplan Viak) have started a partnership to increase their building stock instead of competing (Byggeindustrien, 2021). Though, these are still only two relatively small initiatives in the private sector, which currently is providing in a limited result. A possible way of improving the market strategy could be a national standard for MPs and a governmentally funded marketplace where product volume and transparency will become drivers for a distribution of reusable elements. Once the supply and demand of reused building components is high enough, a private and competitive business can evolve, creating an attractive market that is also economically sustainable.

The lack of documentation is a barrier in creating material passports for existing or soon-to-be renovated or demolished buildings. DOK § 11. Duties of the Commercial Party, states that producers and importers of building materials are only obliged to store documentation of fundamental product properties for 10 years. The properties are for example weight, material type, production year and exposure class etc. SAK10 § 12.6 sets a minimum storage period of 5 years for more detailed documentation, such as element drawings showing geometry and potentially reinforcement (Appendix I – Norwegian legislations for the building industry). These regulations should be changed so that all necessary documentation is available for a longer period. A possible solution is introducing material passports. Current practice of declaring materials in existing structures manually or with tools such GPR is time consuming and results in high costs, limiting the commercial reach.

The introduction of precise and detailed material passports in DfD projects will be beneficial for future renovation or demolition/deconstruction. With all component information stored, including disassembly instructions and location, the considered building will function as a material bank where the owner or externals can extract functional elements for further use. If this building material marketplace is supported by a sufficient library of standardized testing methods such as NS 3682:2022, the predictability around the economical aspect of reuse will significantly improve.

Based on existing research and literary reviews the acknowledgement of material passports has increased the recent years and there is a correlation between the increase in number of scientific papers on material passports and on circular economy. This can indicate an interest regarding the potential of material passports. A possible explanation to this is that MP is expected to be part of the transition to a circular economy in the building industry. In the beginning, the research and implementation of MP were linked to material recycling. The latest scientific results show that direct reuse of components is more a sustainable option. Therefore, the focus has shifted from recycling to reuse. Material passports can play a central role in the development of design for deconstruction methods. The interaction between DfD and MPs can remove the need for laborious work of mapping components for reuse in the future, it will reduce the time of selective deconstruction, and can make used building components easier to commercialize. A synergy between DfD and MPs will therefore provide environmental benefits, create a circular flow of building elements and by this satisfy one of the most fundamental principles in CE, closing the material loop.

Once material passports and a commercial business around reuse is solid, the availability of reused elements is assumed to increase. This is expected to create new opportunities for how reused components are utilized. Currently, reusable members are shaped to fit an already intended design. The research carried out in this thesis indicates that if the market and economic benefits of reuse evolve as expected, there might be a change in how structural design is performed in the future. The prediction is that available members from a stock of elements or from a demolition project will the dictate design of a new building or rehabilitation project.

Stock design is presented by experts in circular building strategies as a possible next step after material passports and design for deconstruction. Stock design will let the available materials dictate design, optimizing the structure for material reuse and by this reduce the GWP. Case studies by Brütting et. al. presents available tools that enables stock design, proving how mathematical simulations results in building structures that satisfies SLS and ULS (Brütting, et al., 2018) (Brütting, et al., 2019) (Brütting, et al., 2020). The environmental benefits of Stock design are considered to be significant, though studies also reveal that the method is sensitive to material type, transport distances, topology of construction site, location/geography and criteria for testing and documentation. The practice of stock design is new and untried in physical projects. In theoretical case studies the method shows satisfying results and can potentially be a part of the shift to a circular economy. Stock design should be a focus area for future research in circular economy in the building industry.

7. Conclusions

The objective of this thesis has been to shed light on the current practice and potential benefits of reuse in the Norwegian construction and infrastructure industry. These aspects have been studied with a methodology of triangulation between a literature review, documentation review, and case studies together with conversations with experts. The following can be concluded after these studies:

Based on high demolition rates, a growing trend of urbanization and the fact that the availability of natural resources is limited, the need for reusable building components will increase in the years to come. Literature and reuse projects reviewed in this study reveals several barriers regarding reuse. The most influential ones are limited standardization regarding testing and certification of building products, and increased costs related to laborious processes such as selective deconstruction and testing. The difficulties regarding product declarations makes it unclear how responsibility and related risk can be dealt with, and the high costs leads to expensive reuse-products that are unattractive in the market. This results in a lack of confidence among owners, designers, and builders in implementing reuse, giving rise to a practice that is not utilizing the full potential of these circular building techniques. Reuse can close the material loop and inhabits an important role in the shift from a linear to a circular economy. It will also reduce virgin material production, minimize waste and by this lower the environmental impact of the building and infrastructure sector. The results obtained from the numerical example and the reuse project in Namsos indicate that reuse have substantial environmental benefits. The very recent incentive arrangement presented by ENOVA is believed to have a positive effect to the development of circular building techniques. Until reuse becomes equally attractive as new products in an economic perspective, these incentives are necessary to make reuse a competitive option.

Reviews of modern scientific literature, official guidelines and national climate strategies are all indicating that design for deconstruction will be important in the transition from a linear to a circular economy in the building industry. Many of the problems that must be dealt with in upstream reuse such as mapping reusable materials in existing buildings, separating elements, and non-destructive deconstruction can be solved by introducing DfD principles in the design phase. Experiences from the building industry is that selective deconstruction is expensive and monolithic connections are problematic. Moreover, this emphasizes the fact that accessible mechanical connections and disassembly plans are essential for a sustainable and circular building design.

Material passports can contain and display important information such as geometrical and mechanical properties, disassembly guidelines and location. This information can provide data that simplifies the deconstruction processes, making reusable elements easier to access and cheaper to distribute. Therefore, a synergy between MP and DfD will support the circular flow of materials, benefitting the business of reusing building components and allow for the practice of using buildings as material banks (BAMB). The idea of a circular flow of materials creates a demand that previously has been of little importance, this is temporary storage of building materials. The current strategy of LEAN production and distribution is counterintuitive to the methods of reuse and DfD in regard of storage. The industry must bridge the gap between LEAN and reuse philosophy to deal with the logistical changes.

Quantifying the reuse potential and its environmental impact has proven to be a comprehensive process. Studies shows that in reuse projects the GHG emissions is sensitive to the building mass and to processes such as deconstruction and transportation. The reuse potential varies between the material type and therefore affects how each case should be evaluated. Of the materials considered in this thesis, steel is considered most applicable to reuse due to good durability, fit for mechanical connections, high yield factor (Y) and low reduction of material quality during recycling. Concrete is large in mass and more dependent on monolithic connections. Though, concrete is the only material that currently has a standardized way of testing and reusing a structural product (hollow core slabs). Limited knowledge about deuteration and aging of modern wood products and adhesives makes the reuse potential of timber hard to evaluate. Still, timber is a material that of substantial use in Norwegian construction practice and the possibilities of reuse should therefore be investigated. Wood based products are light weight and adaptable to mechanical connections. This generates lower emissions from deconstruction and transportation processes compared to the cases with concrete. Timber is therefore predicted to have a big potential in future developments regarding reuse of structural components.

Documents considered important for the reuse practice have been reviewed in this study. National legislations such as TEK17 and DOK present comprehensive criteria regarding the reuse and distribution of used building products. These legislations often serve more as a barrier than a motivation. Documents provided by the industry such as BREEAM NOR v.6.0 and NS 3682:2022 are considered as influential in the implementation of reuse and design for deconstruction. The BREEAM manual is highly influential because of its position in the real-estate market and will therefore motivate the building industry to implement reuse and design for deconstruction principles. The new standard has proven to be useful and have already improved the confidence for reusing hollow core slabs. NS 3682:2022 will lead to the development of more documents standardizing the testing and reuse of structural components. It is expected that the reuse rate of load bearing elements and by this lower the environmental impact of new building projects.

8. Future works

While working on this thesis it has become clear that there are certain parts of this topic that need to be investigated more thoroughly in future research:

- Quantifying the reuse potential has proven to be difficult and it has been explained that there are big differences between the material types such as steel, concrete, and timber. More effort should be put in investigating the possibilities for a more circular use of these products such accessible mechanical connections and if mechanical or other technical properties change during a long period of time.
- The researchers representing timber and steel need to follow in the footsteps on the concrete industry and develop standards for testing and declaring products for reuse. This is essential for the shift from a linear to a circular economy.
- It should be investigated how the BREEAM-NOR v.6.0 manual and the incentive arrangements from ENOVA affect the project development in the years to come. Will it enough, or will the industry need more external pressure before reuse is chosen as an equally attractive option?
- A lot of this thesis is based on theoretical studies and academic articles. It will be important to perform the methods studied such as reuse and DfD in real projects to evaluate the benefits in both environmental and economical perspectives.
- Some of the methods presented are not a common practice but is predicted to be so in the future. Before stock design and using buildings as material banks becomes the norm, the scientific community needs to find ways to put the potential to practice.

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Appendices

A. Appendix I – Norwegian legislations for the building industry

The following appendix will present Norwegian legislations and guidelines that must be considered for DfD and for the implementation of reuse in building projects. During the preliminary study for this thesis, it has not been performed a thorough investigation of the Norwegian legal framework, but an effort has been made to present the most eminent laws and regulations related to reuse of building materials.

A.1. TEK17 – Regulations on technical requirements for construction works:

TEK17 is a regulation containing technical criteria for buildings and presents guidelines for a set of properties that a building needs to inhabit to be built legally in Norway.

TEK17 § 2-1 Documentation to satisfy specifications (2017)**.**

First section:

"*first section highlights that the demand for documentation is related to the completed building. The scope of the documentation for project planning and execution needs to be adjusted to each project individually, depending on type of building, complexity, and risk*".

Third section:

"*Relevant and valid Norwegian Standard or equally valid standard can be used to document that criteria and pre-accepted properties are satisfied. If regulations or pre-accepted properties does not specify standards to be used, it is the party responsible for project planning that needs to consider if a standard is suited and valid to document that criteria or properties is satisfactory. The assessment must be documented (...) criteria to structural integrity can be documented in another way than using the Eurocodes, but this is particularly demanding and in practice unusual. Party responsible for project planning must document in the building application that at the structural safety is at least as good as if the Eurocodes were used*"

TEK17 § 2-4. Documentation of the execution (2017)**.**

"*Products in buildings must have documented properties. In the case of sale of products, the specifications given in the production declaration must be satisfied. Product declaration, included instructions for assembly must be included in the project documentation*"

TEK17 § 3-1. Documentation of building materials for buildings (2017).

"*This legislation complies demands that all building materials that are used in the construction of a building needs to possess satisfying properties, and that this can be documented (...) if it would come to a situation where the product declaration is missing or incorrect, it is necessary to verify that the building material possess the properties necessary so that the completed building satisfies the claims in TEK17 (Norwegian technical building legislation). Verification can be completed through testing or other form of control to define the functional properties*"

TEK17 § 9-5. CDW (construction & demolition waste)

Second section states: "*One should strive for choosing products that are well suited for reuse and recycling*"

Guidelines for the second section: "*a building that is planned, designed, and constructed so that materials and products can be reused, will contribute to reducing waste (...) Products are unfit for reuse and recycling if they contain toxic or other hazardous substances or if they consist of different materialtypes that are hard to separate from one another*"

The guideline in TEK17 further refers to: *DOK* §10 requirement g: "*sustainable use of natural resources*" and further states that reusability is an important property in this context ***(***Appendix I – Norwegian legislations for the building industry***)***.

A.2. Regulations for documentation of building materials, DOK (DiBK, 2016).

In 2014 the Building Material Directory (Byggevareforordringen) decided that most commercial building components for sale in the EEA (European Economic Area) should have documentation declaring product properties, either through CE-certification or product declerations (Sørnes, et al., 2014).

"*DOK is a guideline for the distribution and documentation of products related to the building industry, e.g., building materials, technical installations etc. The guideline contains demands and regulations of CE-certifications of building materials. CE-certification means that a product has been produced based on a harmonized standard or the producer has chosen to have an official European technical certification of the product*".

For products produced before 2014 there is no demand for CE-certification or declaration of performance. Materials that are reused on site in rehabilitation projects will therefore not be affected by the requirements for documentation, this is because the materials never go by the commercial marked but are instead reused locally in a new project (Sørnes, et al., 2014).

§ 1. Documentation of building materials

In this paragraph it is stated that all building materials that is "*produced, sold, marketed and distributed*" for the use in buildings needs to follow the regulations in this legislation. This also affects reused building members and materials (DiBK, 2021). In cases where reused materials don´t have a change in ownership, but the original owner chooses to reuse the element either in the same location or somewhere else, it is not considered to be "*distributed*". This means that the owners, e.g., a city can reuse a building element without being forced to document certain properties or perform tests, though the owner will take the risk when it comes to the performance of these products in the next life cycle (DiBK, 2016).

§ 10. Documentation of fundamental properties *(2016)*.

«*Building materials that is not CE-certified should have properties, when assumed the material are used in a responsible way, contributes to that the building satisfies fundamental requirements when it comes to:*

- ***Mechanical resilience and stability***
- *Fire safety*
- *Hygiene, health, and environment*
- *Safety and accessibility during use*
- *Cover against noise*
- *Energy efficient and insulation*
- ***Sustainable use of natural resources***"

This implies that if a product does not have a CE-certification, but a candidate for redistribution it should, based on, § 10, second section, be considered that "*fundamental requirements (...) are documented relative to the importance of the component's role in the potential building*". In addition to this, "*fundamental requirements (...) should be documented according to a satisfactory technical specification*". To document this, it should be, according to, § 10, third section "*used relevant calculation-, testing- or classification standards*". (2016).

CE-certification alone is usually not a satisfactory documentation. It is often set criteria in Norwegian regulation of supplementing documentation that declares the product´s adaptivity to Norwegian building customs and climate conditions. SINTEF Technical Approval is a supplemental documentation for products that is cleared to be utilized in a scenario specified in the product declaration (Sørnes, et al., 2014). ETA (European Technical Assessment) is a documentation that can be given for products that is not covered by a European technical standard and therefore cannot be CE-certified. In Norway it is SINTEF that has been given the roll of the certifications and distribution of ETA´s (SINTEF, u.d.).

§ 11. Duties of the commercial party (2016)

"*Producer, it´s representative, importer, and distributor, should make sure that the fundamental properties of building materials are documented (...) producers and importers should store documentation related to the product for 10 years after the product has officially been made available on the market for the first time*"

SAK10 § 12.6 Special regulations about responsibility

This regulation is regarding production drawings, e.g., the drawings of a concrete beam and it´s reinforcement.

"The regulation states that documentation must be stored for a minimum of 5 years (...) It is therefore necessary that the responsible parties store the documentation for this amount of time with respect to both consideration as evidence and as a reason to perform an investigation if a malfunction were to occur"

A.3. Summary of the current regulations

It is only one regulation in TEK17 that relates to reuse and material recycling directly, this legislation is also a concern only for new buildings, in other words design for deconstruction (DfD). If a product which is not CE-certified is to be commercially redistributed or marketed, there must be a proof of documentation declaring that a set of properties is satisfying the updated criteria of performance. This can be done through e.g., testing.
As for product documentation it must be stored for at least 10 years after being put out on market.

B. Appendix II – Criteria based on the EU taxonomy

Criteria to do the minimum damage (do no significant harm – DNSH) (The European Commission, 2021)

"*At least 70% of the non-hazardious CDW generated on the building site is prepared for reuse, recycling and other sustainable resourcing of materials based on the waste hierarchy and the EU´s protocol for waste management*"

- Relates to BREEAM-NOR v.6.0 subject category Wst 01 and Mat 06.

"Operators limit generation of waste in building- and demolition processes in guidance with EU´s protocol for waste management. One considers using best practice available. One should use selective demolition techniques to facilitate secure removal of hazardous waste, make reuse easier and to secure high quality recycling through selective removal of materials by using modern recycling systems for CDW"

- Relates to BREEAM-NOR v.6.0 subject category Wst 01 and Mat 06.

"Building design and structural construction techniques makes circularity possible. This is demonstrated particularly, by referring to ***ISO 20887*** *or other standards for the assessment of disassembly or adaptivity of building, how they are designed to be more resource effective, adjustable, flexible, and dismountable to make reuse and recycling plausible"*

- Relates to BREEAM-NOR v.6.0 subject category Mat 06 and Mat 07.

C. Appendix III – FutureBuilt requirements

2.3 reuse of building components for circular buildings (Futurebuilt, 2020)**.**

- As a total at least 50% of the components in the project (by weight) should be reused or be reusable.
- In *new* buildings at least 20% of the components (by weight) should be reused and reusability should be documented for a minimum of 10 component types defined as different building components in level 2 class in regard of the building component schedule illustrated in (figure 29).
- In rehabilitation projects a minimum of 50% of the existing construction (by weight) be contained. Refurbishing the original construction accounts for reuse. In addition to this, at least 10% of the new components added to the project should be reused and a minimum of 5 components (level 2) should be reuse.

Documentation (Futurebuilt, 2020)**.**

- Procedures for quality guarantee and material documentation is to be described. Quality and properties should be documented in a way it satisfies the requirements in TEK and DOK.

Reused mass and type of components should be stated in weight and percentage of the buildings total weight.

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