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Norwegian University of
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Faculty of Architecture and Design
Department of Architecture and Technology

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Design for disassembly in life cycle assessment and circularity evaluation.

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Sustainable architecture
Submission date: May 2023
Supervisor: Patricia Schneider-Martin
Co-supervisor: Carine Lausselet

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Abstract

While the world is facing material scarcity crises, the consumption of material resources is increasing every day. With the building sector being one of the largest consumers of raw materials, reuse of materials and therefore design to disassembly can be vital in building design. Design for disassembly (DfD) can be time-consuming and expensive, although it can result in the conservation of raw material resources. Therefore, finding methods to demonstrate the benefits of DfD may lead to more application of this practice.

This thesis aims to find similarities and differences between LCA-based methods and circularity indicators for implementing DfD in projects. This goal can help to identify which one of the LCA-based methods and circularity evaluation methods can demonstrate the advantages of DfD. As a first step, different LCA-based methods and circularity indicators were reviewed to find the suitable method to incentivize the DfD. Then, three methods were chosen for testing, NS3720, FutureBuilt Zero, and Urban Mining Index.

In this study, three options of a one-unit apartment of the “Treet” building in Norway with different variations were introduced to test the DfD and no DfD variables. The inventory data was collected from different literature searches and Environmental product declarations (EPD). The global warming potential according to NS3720 and FutureBuilt Zero, and the circularity potential based on Urban Mining Index (UMI) of these three options was calculated for two life cycles. The Reduzer software was used as a resource for the results of the first cycle. Based on Dr. Rosen's dissertation and some adaptations to the Norwegian market by a previous master thesis, UMI evaluation calculations of these options were performed.

The results suggest that the DfD method can positively impact the environment more than the standard construction method. Moreover, it indicates that within the assigned system boundaries, all three chosen methods can show the benefits of DfD in projects. However, the choice between prefabricated modules and prefabricated elements remains unclear due to the contrasting results of the methods. The promotion of DfD through LCA methods and circularity indicators will serve as a central tool for developing components with multiple-use cycles, thus it will assist in reducing the extraction of raw materials and the production of waste in the construction sector

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List of Abbreviations

CE	Circular economy	NRW	Nonrenewable
CLP	Closed Loop Potential	O1	Option 1 O1
D/NC	Disposal and non-certified	O2	Option 2 O2
DCCR	Downcycling certified	O3	Option 3 O3
DfD	Designing for disassembly (DfD)	PCR	product category rules
ENCR	Energy recovery certified	PEF	Product Environmental Footprint
EoL	End of life	RCCR	Recycled certified material
EF	Environmental Footprint	RC	Recycling
EPD	Environmental Product Declaration	REACH	Registration, Evaluation, Authorization, and Restriction of Chemicals
FRS	Final retention in society	RSL	Reference service life
GWP	Global warming potential	ReSL	required service life
GHG	Greenhouse gas	RUaEP	Resource Use and Emissions Profile
UOR	in-use occupation ratio	RU	Reusing
LCA	Life cycle assessment	RW	New non- Certified renewable
LCIA	Life Cycle Impact Assessment	RWCR	New Certified renewable
LP	Loop Potential	SD	Selective dismantling
MCI	Material circularity indicator	TH	Time Horizon
MEoL	Material End of Life	UMI	Urban mining Index
MFA	Material flow analysis	UD	usual demolition
MLP	Material Loop Potential	Fv	Value factor,
MRC	Material Recycled Content	Fw	Work factor

1 Introduction

The world is facing material scarcity for future generations, at the same time, the use of material resources has surpassed 100 billion tons, and advances in scientific research are also providing a more detailed but bleaker picture of where the world is likely to go. (The Platform for Accelerating the Circular Economy, 2020) Therefore managing recourses plays a crucial role. The importance of managing resources increases regarding non-renewable sources. The problem with non-renewable materials is that they can turn into waste after a short-term utilization period and be unavailable for further usage. (Moraga et al., 2021) Every average European produce 5 tons of waste every year, from which only 38% is being recycled (European Commission, 2023b) The total waste generation in Norway is 11.58 million tons and the Norwegian construction sector is the biggest single contributor with 25% of the total waste per year. (Statistics Norway, 2022) Of this amount, 55% is recycled, 19% is incinerated with energy recovery and 23% is landfilled. (Lausselet et al., 2023)

Moving from a linear (take-make-waste) to a circular (take-make-reuse) economic model is the answer to the waste challenge. This transition can lead to some benefits such as improvement in resource security and reduction of import reliance; reduction of environmental impact; providing economic growth and opportunities for innovation; and creation of opportunities for sustainable consumer behavior and employment. (European Environment Agency, 2016)

European union (EU) is eager to reduce the consumption of energy, raw-material, and Greenhouse gas (GHG) emissions. (Osti et al., 2017) 40% of annual global CO_2 emissions are generated by the built environment. Of these total emissions, the operation of buildings accounts for 27% per year, while the materials and construction of buildings and infrastructure are responsible for an extra 13% per year. (Architecture 2030, 2023) Norway's goal toward GHG emissions is a 50-55% reduction by 2030 and 90-95% by 2050 compared to emissions in 1990. (Regjering klimaavdeling, 2021) Calculating these emissions can help define measures and solutions for GHGs' short-term and long-term reduction. (Standard Norge, 2018) Moreover, the circular mindset will contribute to the decoupling of economic growth from resource use, thus preserving Europe's natural resources while promoting sustainable growth, and it will allow the European Union to decrease its environmental footprint and increase circularity in the next decade. (European Commission, 2023a)

All in all, the focus is on developing more efficient reusable, and recyclable to reduce and prevent waste production, in other words, less emissions and more circularity (Osti et al., 2017) This can be achieved by developing resilient, reusable, repairable, and recyclable products. (European Commission, 2020) Therefore, considering designing a product that can be disassembled, reused, and recycled at the end of its life can lead to less waste production, less CO2 emission, and a more circular society. (Abuzied et al., 2020) The client/builder/designer can contribute to this by clarification of needs, location, site selection, geometric form of the designed building, construction principles, energy solution, and materials. (Standard Norge, 2021c) Designing for disassembly (DfD) can be one of the solutions for preserving resources. In the next sections, the DfD and the relation to the Life cycle assessment (LCA) and Circular economy (CE) are explained.

1.1 DfD

The EU countries are on their way to achieving the target of 70% recycling in construction and demolition by 2020, with most of the countries already surpassing the target in 2016. (European Environment Agency (EEA), 2020) In the construction industries in Norway, a minimum of 70% of generated waste should be separated into specific types to be delivered to waste process facilities to be reused or recycled. (Byggkvalitet, 2017)

Circular economy introduced a waste pyramid to indicate the actions toward waste. The Waste Pyramid shows that the first step of waste processing for a circular economy is reducing it, the second step is direct reuse, then material recycling. The last two steps in this pyramid are energy recycling and disposal. (Anne Sigrid Nordby, 2020) The main purpose of reusing in the waste pyramid is to preserve material resources, reduce waste in the demolition, and finally reduce GHG emissions. (Anne Sigrid Nordby, 2020) Strategies for waste reduction can be related to the adaptability of the building and recycling mined materials back into the economy. (Anne Sigrid Nordby, 2020) These options can be made possible by designing with future consumption in mind.

Reduce in the waste pyramid: Reduction of waste starts from the planning of the building. The building can be designed in a way that the floor area is used efficiently and sharing space for different functions is encouraged. (Anne Sigrid Nordby, 2020) Another strategy for reducing waste is to increase the lifespan of the materials and their components and design them for their reusability. Regular maintenance plays an important role to reduce waste and increase lifespan. (Anne Sigrid Nordby, 2020) Reducing can lead to less production and therefore less raw material extraction.

Reuse/ Reusability: Reusing in the waste pyramid in the construction industry can mean two things: 1. rehabilitating or retaining a building and 2. reusing the materials and components with their original or new function. (Anne Sigrid Nordby, 2020) Reuse can conserve materials and energy costs by maintaining the integrity and complexity of the material, and can be beneficial for climate change; although it is vague what will happen with building components/materials in the future. (Andresen et al., 2021), (Ellen Macarthur Foundation and Granta Design and Life, 2019)

Some strategies can be used to enhance the reuse of materials. Materials can, for instance, be chosen to be more robust and the connections and joints between them can be flexible and visible. (Anne Sigrid Nordby, 2020) The robustness of materials can be increased by reducing the number of materials and components in a product, using the same material for each product, and using modular design with standard dimensions and less complexity when designing a building component. (Anne Sigrid Nordby, 2020) Reused materials should have good conditions according to TEK and DOK with a long-life span and justify use. (Anne Sigrid Nordby, 2020) Moreover, restricted substances (REACH) which are restricted or banned from being manufactured, should not be used in producing materials/products on the European Union market. (European Chemicals Agency, 2023) This information should be available for manufacturers and designers to make reusability possible, (Anne Sigrid Nordby, 2020) and overall, the possibility of reuse can be increased by designing the materials/components with reusability in mind. (Andresen et al., 2021)

Recycle/ Recyclability: Recycling is a recovery-related activity that transforms waste into products, materials, or substances that can be used for the initial purpose or other purposes.

(Standard Norge, 2021a) When a product cannot be remanufactured, refurbished, or reused, it can be recycled, although the complexity and integrity will be changed.

Regarding recycling processes, they can be upcycling and downcycling processes. When a product gets value by being processed, developed, and used as a new component, it is called upcycling, (Anne Sigrid Nordby, 2020) Whereas when a product losses some of its properties and is used again as a raw material, it is called downcycling. (Ellen Macarthur Foundation and Granta Design and Life, 2019) Recycling efficiency can be increased by choosing the materials which have potential, reducing the number of materials in one component, not including hazardous substances, design products for dismantling before material recovery in the recycling process. Although recycling efficiency has limitations due to changing values based on technology, demand, and application.(Ellen Macarthur Foundation and Granta Design and Life, 2019) in general, recycling can benefit producers by selling the recycled product to third parties and earning money, and reusing the recycled material itself to save energy and material. (Ellen Macarthur Foundation and Granta Design and Life, 2019)

Overall, a common strategy of designing material by thinking about future uses and how it will be manufactured and deconstructed arises when considering reduce, reuse, and recycle, in other words, Design for Disassembly (DfD). Figure 1

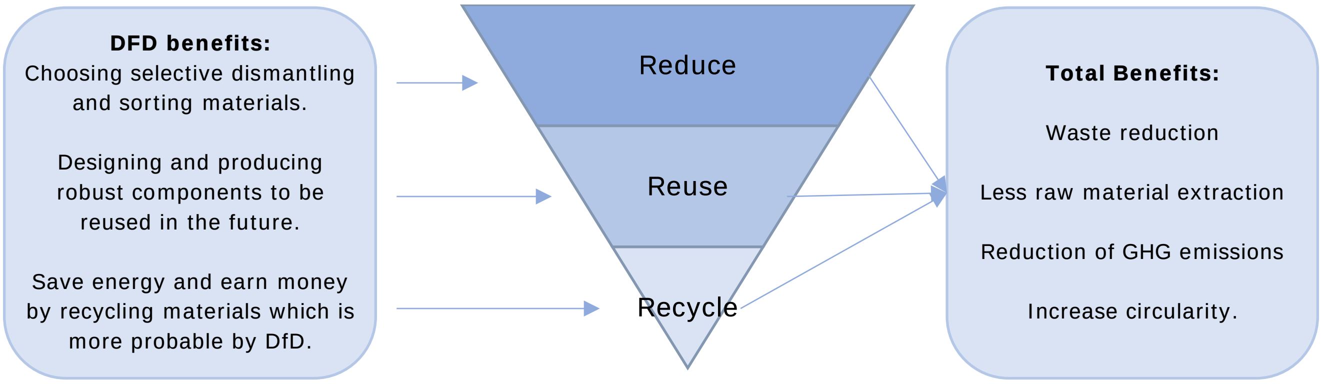


Figure 1 The 3Rs in circularity and DfD

Design for Disassembly is a method of developing a component/product in such a way as to facilitate its disassembly for maintenance, repair, recovery, and reuse of materials/products. (Yoga Mule, 2012) DfD, by enabling advanced technologies and supporting innovative product development cycles by organizations, can minimize the environmental impact and improve the value of end-of-life products. (Yoga Mule, 2012)

Although implementing the DfD strategy in the design process can improve product sustainability (Osti et al., 2017), it is considered a time-consuming, difficult, and expensive approach. (Carrell et al., 2009) By DfD, the production cost will decrease; however, some extra costs will be added to the process. For example, costs of collection and reverse logistics (in particular labor and transportation), costs of treatment (e.g. remanufacturing or recycling process) for DfD, and/or initial design or R&D investment/marketing cost. (Ellen Macarthur Foundation and Granta Design and Life, 2019) Through the inclusion of DfD, the designers should select the materials and components based on the end-of-life scenarios and propose the disassembly process and the efficiency of this system. (Go et al., 2010) Then, at the end of the life of the components, the proposed disassembly system should be implemented. Moreover, the higher the cost of disassembly, segregation, and sorting of materials, can be less economical. (Rosen, 2022) Therefore, all these processes can be economically inefficient and limit the choice of DfD in the early design phases.

Time is another barrier to dismantling, and when time is critical, selective dismantling may not be a viable alternative to demolition. (Cruz et al., 2015) However, some techniques of DfD can reduce time consumption. DfD can establish a pre-construction planning phase with the proper required documentation, such as plans, inventories, and labeled materials without hazardous substances, to facilitate the deconstruction and materials recovery processes. (Cruz et al., 2015) DfD can also provide training methods for the construction team and help to increase their productivity. (Cruz et al., 2015) Therefore, the DfD is viable when it is cost-efficient, technically possible, and well-documented, and to better evaluate the use of DfD, several aspects of this system should be considered.

One of these aspects can be providing incentives to priories the less-emission-driven solutions in the construction industry. This can be possible with methods including time, technology, and circularity. (Andresen et al., 2021) These incentives can prove the worthiness of DfD by quantifying the impact of DfD on the environment. Standards and indicators are defined to show a product's sustainability, carbon footprint, and circularity. These factors can evaluate DfD from different perspectives. Therefore, analyzing these indicators and their similarities and differences can influence selecting or not selecting DfD.

A circular economy mindset in societies can ensure the efficient consumption of resources.(Rasmussen et al., 2019) In addition, LCA is an efficient tool to evaluate the environmental performance of components and lead them toward a circular economy. (Haupt & Zschokke, 2017) Therefore, Life cycle analysis and circular economy can provide indexes for evaluating DfD; however, various methods and indicators should be examined to check their impact on DfD. The next section will explain more about these methods and indicators.

1.2 Life cycle analysis and DfD

There is a need to significantly reduce the environmental impact of the built environment. LCA is an internationally accepted methodology to help achieve this goal. (Sahar Mirzaie, Mihaela Thuring, 2020) UN Environment Assembly (UNEA4) emphasizes the importance of Life cycle approaches including LCA for achieving sustainable consumption and production, increasing resource efficiency, and reducing risk from harmful materials. (United Nations Environment Programme, 2019) To accelerate the transition to more sustainable consumption and production patterns, LCA is the most reliable tool to provide the system perspective. (United Nations Environment Programme, 2019)

The environmental aspects and potential impacts of a product during its life cycle are mentioned in the LCA, and collects these burdens and impacts starting from the material production phase, then the use phase, and finally during the End of life (EoL) scenarios. (Standard Norge, 2006) Therefore, the greenhouse gas calculations attempt to provide the potential of identification and then reduction of the emissions in the short and long term.(Standard Norge, 2018) Therefore, LCA can help with reducing emissions from various sectors by acknowledging the amount of it through doing a deep life cycle analysis.

Moreover, LCA results can help 1. to point out the possibilities to improve the performance of materials in their lifespan, 2. to inform decision-makers about planning, design, or redesign processes and purposes. 3. to select environmental performance indicators and measurements, and 4. to brand products by giving labels to more environmental-friendly ones and enhancing their demand 5. To document the impact of product 6. To explanate of achievement of the requirements and goals. (Standard Norge, 2006), (Standard Norge, 2018)

The amount of emission and waste can be reduced by DfD and minimizing the cuts and waste in the life cycle of a building. (Andresen et al., 2021) These cuts and waste belong to the construction stage, maintenance, repair, replacement, and refurbishment which can be limited by DfD. (Andresen et al., 2021) In addition, when products are being used from previous projects, they contribute to the reduction of the emissions caused by waste management and production phases (Andresen et al., 2021) On the other hand, LCA results, can be a proper measurement of the impact of DfD in the building's life cycle. LCA methods are based on one cycle, although if assumed two cycles for the evaluation, DfD can be explained based on Figure 2. In Figure 2, the red dotted line shows the production to construction stages of a building, and arrows indicate the possible material movements from the stages of the first cycle toward stages in the second cycle. Two main movements regarding DfD and LCA, are avoiding the C4 to waste and increasing the C1 to A5 material transfer. Thus, DfD in LCA with circularity tries to omit all the waste processing and production stages, and DfD can influence the GHG emissions and results of LCA. Therefore, this study tries to find out the relationship between the DfD and LCA methods.

A1= Raw material Supply
A2= Transport
A3= Production
A4= Transport
A5= Construction, building and assembly work
B4= Replacement
B5= Refurbishment

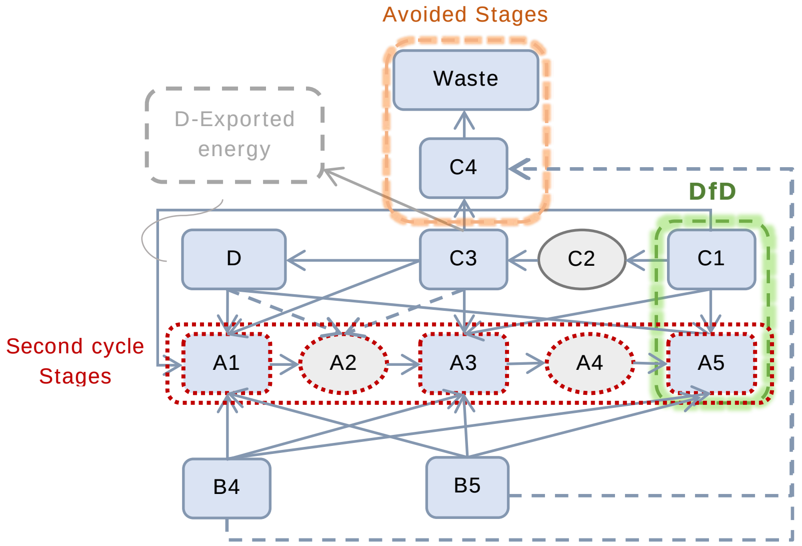


Figure 2 DfD and LCA system boundary

1.3 Circular economy and DfD

The main concepts of CE can be grouped into three main points: designing out waste and pollution, using products and materials to last, and restoring natural systems. (Ellen Macarthur Foundation and Granta Design and Life, 2019) CE can bring some benefits by introducing indicators. For example, at the product level, they can be beneficial for product design, internal reporting, or defining goals for procurement. (Rigamonti & Mancini, 2021) In addition, at the organizational level, indicators can be applied for internal purposes to measure progress or compare different product lines. (Rigamonti & Mancini, 2021)

CE tries to encourage the use of renewable energy sources as much as possible and to promote any activity that can have a positive impact on saving energy and using less labor and materials. (Ellen Macarthur Foundation and Granta Design and Life, 2019) This can be possible by resilient, reusable, remanufacturable, and recyclable materials/ products/ components. (Ellen Macarthur Foundation and Granta Design and Life, 2019) Moreover, CE at the company level provides companies to add additional value to their products and minimize the risk of price changes and material supply changes. (Ellen Macarthur Foundation and Granta Design and Life, 2019) In contrast to a linear economy, it is about optimizing systems rather than components. This involves managing materials in both biological and technical closed-loop systems. (Ellen Macarthur Foundation and Granta Design and Life, 2015) In technical cycles, CE includes maintenance, reuse, refurbishment, and recycling options, while in biological cycles, non-toxic materials are cascaded and eventually returned to the soil, recovering the natural capital. (Ellen Macarthur Foundation and Granta Design and Life, 2015) (Figure 3)

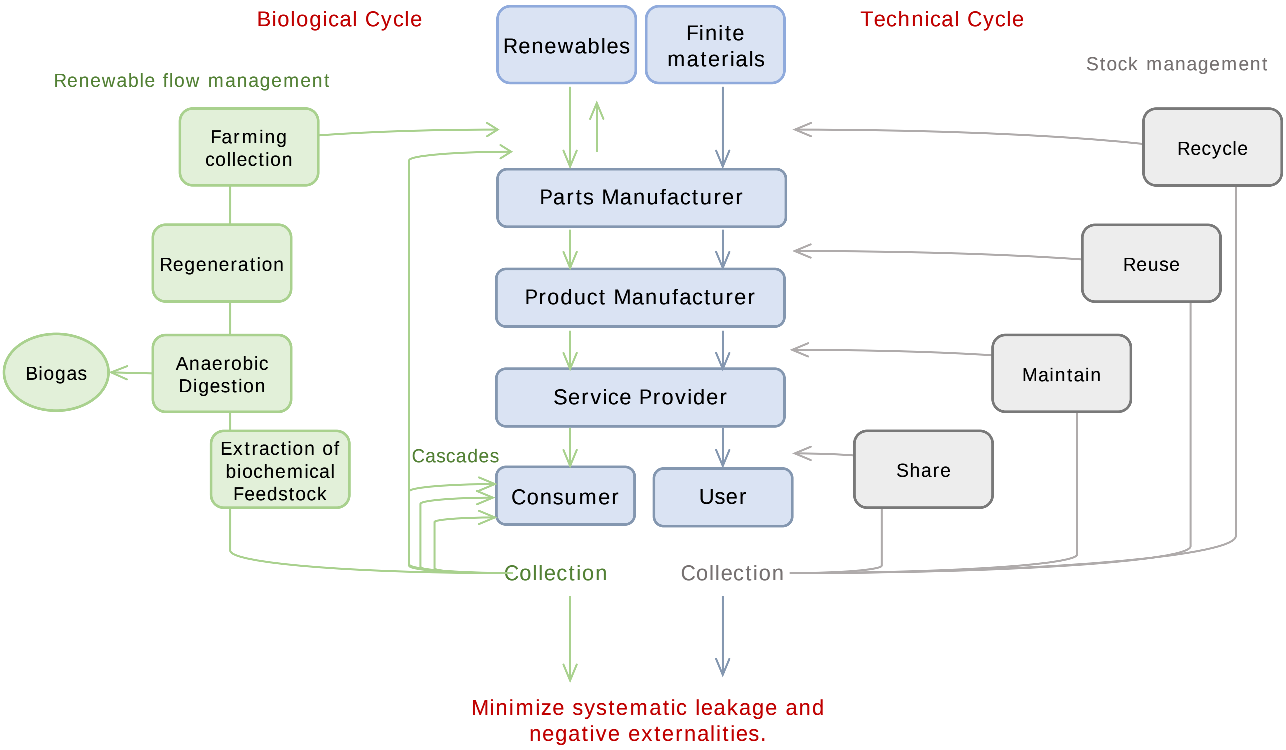


Figure 3 Cycles in the circular economy, Source (Ellen MacArthur Foundation, 2019)

CE promotes the anticipated portion of the total building mass, which will be able to withstand additional cycles after the use phase. In this way, the construction industry can operate continuously in a closed cycle, reducing embodied emissions and energy in production, and new construction projects do not require the raw production of new/raw materials. Thus, it is important to adopt a circular economy in the building industry. This can be done by considering EoL scenarios so that reuse, recycling, and energy recovery can be identified and encouraged. (Sahar Mirzaie, Mihaela Thuring, 2020)

When DfD is applied in construction, building components are designed to be easily dismantled after their use phase, so that they can be removed from the waste system and reused, either in direct use or via material recovery. (Lausselet et al., 2023) This reduces the risk of product damage and loss of value in successive life cycles while increasing product adaptability, endurance, and reusability. (Lausselet et al., 2023)

Figure 4 explains the system boundary of CE. The phases are production, construction, use, and finally end-of-life. The influence of DfD and how DfD can be included in a cycle is shown by the green dashed line in this figure. In addition, the orange dashed line shows the stages that should be avoided in the DfD, which is sending materials to landfills.

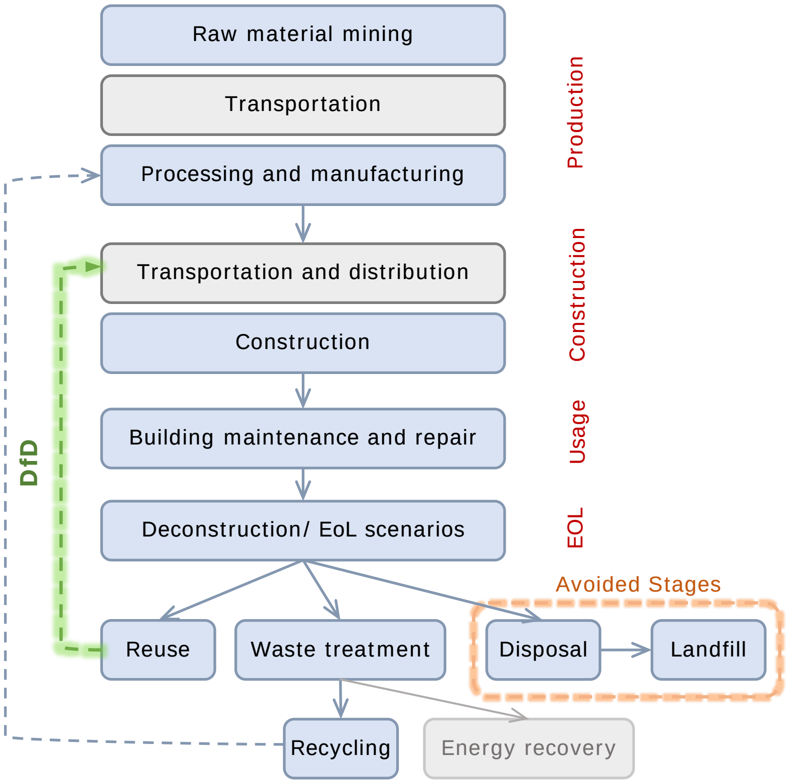


Figure 4 DfD and CE cycle, adapted from (Akinade et al., 2020), and the author's assessment

Achieving CE in the building sector will require a shift in the product life cycle framework, where building components and materials should be designed for future disassembly and reuse. Furthermore, the entire building can be designed for reuse. DFD can provide a central tool to design a building as a donor with easily replaceable components and materials. (Volfova, 2022) This thesis will examine the impact of circularity indexes by applying one of them to a case study. The next Section explains the different LCA-based on CE-Based methods and their comparison regarding their approach toward DfD.

2 LCA methods and Circularity indicators

2.1 LCA methods

Risk evaluation, environmental performance assessment, environmental monitoring, and assessment of environmental impacts are only a few of the environmental management strategies that can be used by LCA, although, LCA may not always be the best alternative, because it does not include aspects such as economic or social. (Standard Norge, 2006) Therefore, it is important to choose the correct LCA method for each project to understand the possibilities and limitations of the results coming from the analysis. (Standard Norge, 2021c)

LCA methods can be applied to all or selected phases of the life cycle of new or existing buildings, for maintenance and rehabilitation, and individual components, elements, or the entire building. (Standard Norge, 2021c) Generally in all these methods, to do a deep Life cycle analysis first the aim and scope of the project should be defined, then the inventory should be analyzed for doing an impact assessment, and finally, the results should be interpreted. (Standard Norge, 2006) Many of the LCA methods share similar definitions which is explained in Appendix 1. Figure 5 illustrates the 6 LCA-based methods/ standards and their connections, and their similarities and differences are discussed in the next subsections.

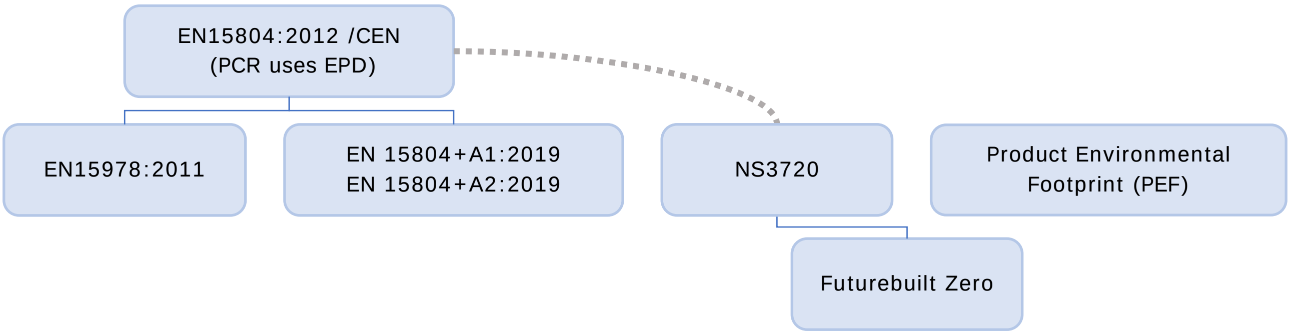


Figure 5 the selected LCA- based calculation methods/standards

EN15804:2012/ EN 15804+A2:2019 EPD

Definition and aims: For all construction products and services, the EN15804 provides core product category rules (PCR), and a framework to ensure that all Environmental Product Declarations (EPDs) for construction products, services, and processes are developed, validated, and reported in a harmonized manner. (Norsk Standard, 2019) Allocations, data collection, generic data assessment, quality of data, indicators, and transparency requirements in EN15804 are based on ISO14044. (Norsk Standard, 2019) Thus, the other CEN standards such as EN15978, EN15804+A2, and Norwegian standards NS3720 and Futurebuilt Zero, which are derived from this standard follow the same requirements.

Indicators: In this standard, environmental impact information is provided using Life Cycle Impact Assessment (LCIA), impact category indicators, and characterization factors in an LCIA according to ISO 14044. (Standard Norge, 2021b) The indicators are divided into four categories calculating 100 years horizon based on data from on Intergovernmental Panel on Climate Change International (IPCC). These groups are 1. Environmental impact indicators 2. Resource use indicators 3. Waste describing indicators 4. Output flow leaving the system describing indicators. (Norsk Standard, 2019) The environmental impact indicators in this standard are climate change (total, fossil, biogenic, land-use land land-use change(luluc)), Ozone Depletion, Acidification, Eutrophication (aquatic freshwater, aquatic marine, terrestrial), Photochemical ozone formation, Depletion of abiotic resources (minerals and metals, fossil fuels), Water use. (Norsk Standard, 2019) This thesis's focus will be on the first indicator, climate change total calculating Global warming potential total (GWP total). GWP total is the combination of the GWPs of fossil, biogenic, and luluc.

System boundary and allocation: The modular system boundary in the last updated version, EN15804+A2:2019, allows data packages to be easily organized and expressed throughout the product lifecycle. It covers the production, construction, use, end-of-life stages, and benefits and loads beyond the system boundary (A1-A3. A4-A5, B1-B7, C1-C4, and D). (Norsk Standard, 2019) Moreover, the allocation in this standard among modules is based on two principles: the modularity principle and the polluter pays principle. Both principles refer to the allocation of product environmental performance impacts and waste management emissions to the module in the life cycle where they occur. (Norsk Standard, 2019) These module calculations are time-related, and the reference study period, service life, replacement period, working hours, and pattern of use should be determined to conduct the assessment. (Norsk Standard, 2019)

EoL, DfD, and EN15804: In a closed loop, the number of secondary output materials with these characteristics and the ability to substitution the primary products should be assigned in A1-A3 next cycle and not the module D. (Norsk Standard, 2019) However, in one cycle, in CEN standards all benefits from A1, A2, A5, B3, B4, C2, C3, and C4 are included in Module D, and reported separately. [21] Module D acknowledges the concept of " designing for reuse, recycling, and recovery" for constructions by identifying the possible benefits of preventing the use of primary materials and fuels in the future while considering the loads associated with the recycling and recovery processes beyond the system boundary. (Norsk Standard, 2019) Therefore, this module shows the benefits of the second cycle.

To gain this benefit, reusable and recyclable materials should be chosen correctly and based on detailed considerations from the beginning, in other words, DfD. These secondary products should have some characteristics. The recovered product should be 1. commonly used for certain purposes, 2. have an identified market or demand, 3. meet the technical conditions for the specific purposes and comply with existing legislation and standards, and 4. its use should not lead to overall harmful effects on the environment or human health. (Norsk Standard, 2019)

In this standard, the “Decision-tree for end-of-waste diagram”, [24, p.59] shows that applying the DfD should be included from the beginning. However, in this diagram, the energy recovery of materials is considered a benefit included in module D, and only materials with more than 60% efficiency in incineration can be included. (Norsk Standard, 2019) On the other hand, in DfD the focus is more on the reusing of materials, which is not considered a high priority in the decision tree.

EN15978:2011

Definition and aims: This standard can be applied to new and existing buildings, as well as renovations, and provides a methodology for evaluating a building's environmental performance and a framework for reporting and communicating the results. This time-related assessment covers all construction products, procedures, and services in a life cycle of a building.(Standard Norge, 2011) Data on the products to be calculated with EN15978 should come from the building's descriptions, scenarios in EPDs the related standard (EN15804), expert assumptions, and LCA studies. (Standard Norge, 2011) The basis of assessment in this method/standard is transparency and traceability of the data, which is presented in sufficient detail to allow the reader to assess the quality. (Standard Norge, 2011)

Indicators, system boundary, and allocation: EN15978 covers the same indicators as EN15804, except for the water use in the environmental impact indicators, and it does not include the calculation's methodology. (Standard Norge, 2011) Moreover, the system boundary of this assessment method follows EN15804 including A1-A3, A4-A5, B1-B7, C1-C4, and D, and the allocation is the modular principle. (Standard Norge, 2011) In this system boundary, the A1-A3 should be used the same amounts as in the EPD, while the A4-C4 can be consistent and based on technically and economically achievable scenarios. (Standard Norge, 2011) EN15978 also follows the modularity and polluter pays principles, therefore it allocates the emissions to the module they happen.

EoL, DfD, and EN15978: The EN15978 approach is designed for a single building or a single cycle of use. (Lausselet et al., 2023) Throughout this lifecycle, there are some losses during the building's life cycle that should be calculated in EN15978. These losses are 1. loss/damage in transport, 2. loss/damage on site, 3. losses during construction, 3. design losses due to the dimensional ratio in the design and product dimensions, and 4. minimum order requirements. (Standard Norge, 2011) These losses can be minimized by DfD, where the components are designed in the correct form to be dismantled without a lot of material waste.

In this standard, module D acknowledges the design for reuse and recycling and helps in the transparency of the net benefit or net burden to the environment resulting from reuse, recycling, and energy recovery. (Standard Norge, 2011)

NS3720:2018

Definition and aims: NS 3720 provides a static method to calculate the GHG emissions from the entire lifecycle of a building, including products, goods, and services related to the construction, operation, use, and disposal of the building in Norway. (Standard Norge, 2018) NS3720 is based on time-related scenarios which cover maintenance, replacement, and other periodic operations. This standard considers the building's required service life (Req SL) 60 years if the client does not say otherwise, whereas the other two standards do not specify Req SL. During this ReqSL of the building, there are changes, such as technological improvements and reductions in emissions per kilometer driven, as well as changes in regulations and taxation. (Standard Norge, 2018) It is therefore necessary to develop a scenarios that reflects technological developments and the fleet composition. (Standard Norge, 2018)

Indicators, system boundary, and allocation: This standard is based on EN15804 and EN15978. Therefore, there are many similarities between these standards and NS3720. The indicators and allocations are based on EN15804, and the system boundary includes almost the same modules as EN15804, except omitting the B7 (water use), and A5 divisions to consequences of site development, groundwork, and the erection of the building, and adding B8 (transport in operation). (Standard Norge, 2021c) Moreover, it calculates the GWP for 100 years based on the UN climate panel’s definition of GHG and follows the same modular and polluter pays principles. (Standard Norge, 2018)

EoL, DfD, and NS3720: To make waste into a resource it is necessary to develop scenarios for the final processing of the various types of waste, based on the relevant statistics for the treatment of construction waste and the current technology for the various types of process. These scenarios can change the module of accounting emissions from C4 to D. Regarding module D, the definition and calculation are based on EN15804. (Standard Norge, 2018)

It is best to decide whether to reuse materials after the first cycle when the concept is developed. The project implementation model in the NS3720 guide is a collaborative effort between the client, architect, contractor, and public sector. (Standard Norge, 2021c) Their decisions can affect the future scenarios of the project, and applying reusable and recyclable materials should be considered in most phases of construction. For example, if DfD is considered, based on the table in guidance of NS3720, (Standard Norge, 2021c, p. 5) in the first stage the client can decide on the flexibility and shareability of the building; in the third stage the architect can choose the reusable materials; in the fourth stage the consultant can provide solutions to meet the high goal of DfD and the client can ensure the application of these solutions; in the fifth stage, the contractor can select the products and their assembly model based on the design and ensure the construction of the building based on documentation. Moreover, NS3720 mentions that if a product has a special assembly method, as should be the case in DfD, the representativeness of the scenario should be checked first, then the scenarios based on PCR, and if no data is available, data from similar construction projects. (Standard Norge, 2021c)

Futurebuilt Zero

Definition, aims, and system boundary: FutureBuilt Zero includes the potential emission benefits of carbon sequestration, material reuse, recycling, and energy recovery, and provides maximum emission benchmarks for a building's contribution to global warming over its lifetime. (Resch et al., 2021) This method is derived from NS 3720 using the same modules in the building’s lifetime, 60 years. NS3720 calculations provide flexibility in system boundaries and scenarios to meet the calculation purpose, and the FutureBuilt Zero method can be assumed as a specific scenario in NS3720 while introducing weighing factors, time, and technology factors. (Andresen et al., 2021) The FBZ method provides more complete calculations on dynamic LCA. This not only incentivizes current solutions and emissions in the short term but also ensures GHG reductions in the long term. (Andresen et al., 2021)

Calculation factors, and allocations: Time factor: The time factor recognizes that emissions reductions must occur within a specified period to meet climate goals, and weights emissions and absorptions that occur in the future less significantly than those that occur today.(Andresen et al., 2021) This is because emissions produced today remain in the atmosphere for a longer time and contribute more to global warming than emissions produced further in the future. (Andresen et al., 2021) This factor is based on dynamic LCA and GWP op to 100 years, and it can be simplified to a sufficiently accurate average time factor, instead of using an annual time weighing factor. (Andresen et al., 2021) Using the more accurate annual time weight results in a time weight 3-18% higher than these average weights, which is too high an estimate. (Andresen et al., 2021)

The technology factor: The technology factor explains the ongoing development of the technology. (Andresen et al., 2021) This factor can lead to a reduction in emissions from materials through technological developments in materials technology, production technology, recycling rates, transport technology, and electrification, together with a decarbonization of the energy network sectors.(Andresen et al., 2021) FutureBuilt Zero uses a simplified and sufficiently accurate average technology factor of 60 years, an improvement of 1% per year is assigned in material production based on historical developments in Norway. (Andresen et al., 2021)

If building materials are reusable, an emission reduction factor is given to calculations in Futurebuilt. FutureBuilt Zero gives incentives for using reuse materials by accounting for 80% of production emissions, and reusability in calculations is credited with reducing material production emissions by 10%, by considering technology and time weights. (Andresen et al., 2021) Moreover, in this method, the energy recovery and production are calculated with 50:50 allocation, and besides that Futurebuilt zero also follows the cut-off 100:0 allocations. (Andresen et al., 2021)

EoL, DfD, and FutureBuilt Zero: While NS3720 does not explicitly explain circularity, FutureBuilt Zero mentions circularity and circular building and provides a framework. Moreover, it mentions that resource consumption in the future should be planned in the building phase. (Anne Sigrid Nordby, 2020) Therefore, five points should be considered in a circular building: First, the reason behind rehabilitation or demolition should be environmentally reasoned if there are existing buildings on the site; Second, the resources should be utilized carefully in the demolition and construction phases; Third and fourth, the components should be reused materials and reusable; the last, the building should have the ability to adapt. (Anne Sigrid Nordby, 2020)

In the FutureBuilt zero circular buildings, a minimum of half of the resources should be reused or reusable. (Anne Sigrid Nordby, 2020) In a new building, at least 20% of products in 10 component types must be reusable. In rehabilitation projects, at least 10 % of products within min. of 5 component types must be reusable. (Anne Sigrid Nordby, 2020) Achieving these factors can be possible by DfD because it helps to plan these fractions of materials' origin from the beginning.

As mentioned before, the cuttings and waste in EoL should be limited and some strategies should be used to encourage reuse. Agreements and technological developments can lead to materials for reusability which can be one of the aspects of DfD. By evaluating components for their potential for reuse early in the design process, reusability can become apparent to demolishers and designers of future buildings. (Anne Sigrid Nordby, 2020) The reusable components in the project should be available for others or returned to the producer, if possible. (Anne Sigrid Nordby, 2020)

Dismantling and demolition take time, and therefore, for reusing components, there should be documents about the specific methods of dismantling and workers should be informed before the demolition starts. (Anne Sigrid Nordby, 2020) FutureBuilt Zero mentions that if a product wants to be reusable it should be documented properly, in a way that information including materials and components, attachment types and points, and building geometry with open BIM should be included in the material passport of that product. (Anne Sigrid Nordby, 2020) These materials should be robust and homogenous without hazardous substances, components containing these materials should have the potential of dismantling without damage, and the kind of construction that allows them to be disassembled independently of connected layers. (Anne Sigrid Nordby, 2020) Therefore, it can be assumed that Futurebuilt Zero is one of the CEN-based methods that can provide more incentives for DfD.

Product Environmental Footprint (PEF)

Definition and aims: The Product Environmental Footprint (PEF) aims to reduce the environmental impact of a product or service throughout its life cycle, by providing a multicriteria measure of the environmental performance. (EC-JRC, 2012) In order to provide the necessary basis for decision-makers, PEF studies should be relevant, complete (all relevant material/energy flows), consistent, accurate, and transparent. (EC-JRC, 2012) The PEF method uses the Product Environmental Footprint Category Rules (PEFCR). The PEFCR was defined for certain products, including some building products such as thermal insulation, piping systems, solar photovoltaic modules, metal sheets, and decorative paints.(Carolin Spirinckx, Mihaela Thuring, Karen Allacker, 2018) Moreover, the results of the PEF should be evaluated to assess the impact of supply chain hot spots/weak spots at the input/output, process, and supply chain phases, and to evaluate possible enhancements. (EC-JRC, 2012)

Indicators: Environmental Footprint (EF) impact categories identify specific classes of impacts addressed in a PEF study, and their evaluation aims to group and aggregate the inventoried Resource Use and Emissions Profile (RUaEP) data based on their corresponding shares of each EF impact category. (EC-JRC, 2012) These categories are Climate Change, Ozone Depletion, Ecotoxicity for aquatic freshwater, Human Toxicity (cancer effects- noncancer effects), Particulate matter/respiratory inorganics, Ionizing radiation-human health effects, Photochemical Ozone formation, Acidification, Eutrophication (terrestrial- aquatic), resource depletion (water- mineral/ fossil), Land transformation. (EC-JRC, 2012) the impact categories in PEF are so similar to other LCA-based methods. Generally, this method also refers to the ILCD Handbook “Framework and requirements for LCIA models and indicators”, “Analysis of existing Environmental Assessment methodologies for use in LCA” and “Recommendation for life cycle impact assessment in the European context”.

System boundary: System boundary diagrams or flow diagrams are recommended to include in PEF studies. The system boundary in PEF follows the same cradle-to-grave principle of the previously mentioned methods because it is an LCA-based method. The PEF system boundary covers all stages from raw material mining to processing, manufacturing, distribution, storing, use phase, and end-of-life processing of the product. (EC-JRC, 2012) The process in this system boundary is divided to foreground and background processes, depending on the data accessibility. (EC-JRC, 2012)

EoL, DfD, and PEF: In the additional data provided by PEF studies, the Information on the ability of disassembly, recyclability, recoverability, reusability, and resource efficiency should be available. (EC-JRC, 2012)Therefore, the DfD potential can be demonstrated from the results of PEF studies.

PEF calculations become complex by adding a reuse, recycled, or energy recovery of products. (EC-JRC, 2012) RUaEP refers to two types of loops when it comes to circularity, the open loop, and the closed-loop. The term "closed loop" refers to the recycling of material from one product line back into the same product line, whereas "open loop" refers to the recycling of some or all of the material from one product line into another product line. (EC-JRC, 2012) Based on these loops, RUaEP provides a formula to include the credits from reused, recycled, or energy recovery of products. However, in these calculations, reusing is included in the recycling part of input materials next to virgin materials in formulas. (EC-JRC, 2012)

Carbon Footprint Formula (CFF) has been defined to balance the environmental impacts of the production and disposal stages of the first and final use of the product, as well as the environmental impacts of reusing the product in subsequent uses. (European Commission, 2017) CFF is based on the situation in the market, targeted at policy decision-making and promoting new reuse/recycling market opportunities. (De Wolf et al., 2020) This formula encourages LCA actors to include reused elements in their projects or to design with reuse in mind for future cycles. (De Wolf et al., 2020)

Comparison of LCA methods

LCA-based calculations share some similarities and differences. Some elements in ISO14044-based methods (EN15804, and therefore EN15978, NS3720, and Futurebuilt Zero), have been harmonized with the PEF methodology to ensure that they produce similar results. (The Norwegian EPD Foundation, 2021) For example, the declared indicators and methods used based on LCIA; the assessment of data quality in the LCA report; the use of certain quality factors in the PEF for end-of-life allocation, and the CFF in the A2 module to define the differences in quality between primary and secondary resources. (The Norwegian EPD Foundation, 2021) However, there are some other similarities and differences, which are explained in this section.

ISO14044-based and PEF methods: They both choose the communication target to be business-to-business and business–to–consumer; and try to improve the products' environmental performance by providing comparative and additional statements and requirements (ISO14044-base) and identifying hot spots (PEF). (EC-JRC, 2012) The ISO14044-based methods have defined system boundary, covering the production, construction, use, and EoL phases (cradle to grave) and the system boundary can be defined based on the studies goal, but including the production phases, while in PEF studies the cradle to grave system boundary should be covered and it can be changed if specified in PEFCRs. (EC-JRC, 2012)

ISO14044-based and PEF calculations choose the functional unit to define all the goals and aspects of the evaluation, although PEF provides some questions defining the functional unit. The functional unit in PEF covers these questions: What are the function and service? How much is the scope of the study? How long lifetime does the study consider? and how well does the result quality can be? (EC-JRC, 2012) Moreover, by looking into the cut-offs in the calculations, they are allowed to be less than 5% in ISO14044-based methods, while they are not acceptable in PEF studies. In addition, carbon storage and delayed emissions are not included in the PEF studies for default impact categories, however, in ISO14044-based methods, these negative emissions are included.

EN15804, EN15978, and NS3720: These three methods use static LCA calculations on an almost similar linear system boundary. These methods share the same requirements as EoL scenarios and allocation principles, modularity, and polluter pays principles. However, NS3720:2018 calculates only GHG emissions in 60 years, while EN15804 and EN15978 calculate the environmental performance of buildings based on defined service life in EPDs or provided data sources.

NS3720 and FutureBuilt Zero: NS 3720 and FutureBuilt Zero both describe a calculation method for greenhouse gas calculations for buildings and to a lesser extent provide fixed system limits and procedures. They calculate the GHG emissions based on 100 year of emissions assessment period based on IPCC and give a service life of 60 years to buildings. However, NS3720 has a broader scope for calculating static LCA, while FutureBuilt Zero has a fixed dynamic LCA-based calculation scope with a defined system boundary, including more emission sources and life cycle modules.

Regarding EoL, FutureBuilt zero includes compensating effects from reusability and exported energy in the main result, while NS 3720 considers these as additional effects in module D. Moreover, NS 3720 refers to waste management as a whole and includes all activities until the waste ceases to be waste. In FutureBuilt Zero, only waste incineration is included. Looking into allocations for reuse and reusability, FutureBuilt defines a simple allocation for reuse and reusability using a simplified average number with accounting for the time and technological developments, and NS3720 includes only technological developments for electricity.

Carbon storage allocation differs in these two methods. NS 3720 includes carbon absorbed in the products, such as carbonation of cement-based products, in the calculations of Modules B1, C3, and C4, as well as Module D, while FutureBuilt only includes these effects over the life of the building, i.e., in Module B1.

Overall, these variations may cause different results that may or may not be comparable. However, by acknowledging them, the interpretation of the results can be reliable.

2.2 CE evaluation methods

CE tries to reduce the negative effects of economic activities on the environment (human/natural) with economic reveals and designing out these impacts. (Ellen Macarthur Foundation and Granta Design and Life, 2015) Circularity indicators can evaluate a product's performance in the CE context. (Ellen Macarthur Foundation and Granta Design and Life, 2019) CE indicators are needed to allow companies to realize their product's linear or circular flow. (Ellen Macarthur Foundation and Granta Design and Life, 2019) Assessing the products from one company with the CE indicator makes the decision-making process faster in this boundary, it can be not so efficient when it comes to policy making and society. Therefore, previous and future use of materials should be considered in broader cycles with sequential and parallel configurations. This should illustrate the materials' supply, use, hibernation, and dissipation along these supply chains. (Moraga et al., 2021) The Circularity indicators can be a basis and input in design decisions. For example, they can be used to compare different scenarios of a product's circularity in the early stages. or it can lead the production toward a more circular approach. (Ellen Macarthur Foundation and Granta Design and Life, 2019) These are some of the evaluation methods which is discussed in the next chapters. (Figure 6)

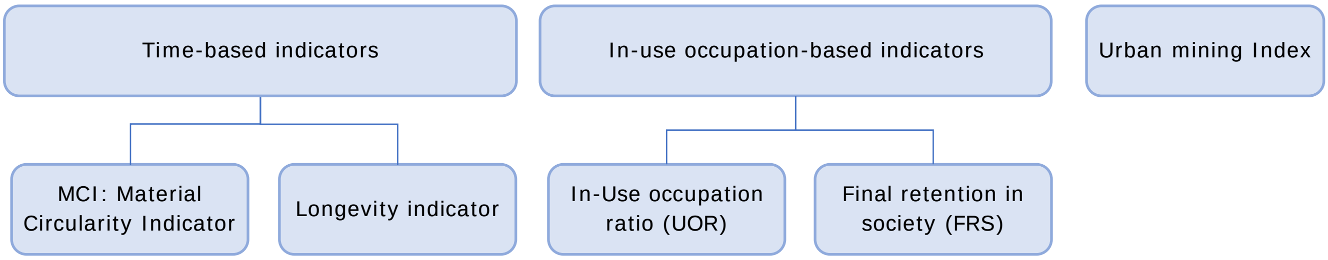


Figure 6 The selected Circularity evaluation methods

Time-based indicators: MCI and Longevity Indicator

Ellen Macarthur Foundation provides two circularity indicators: the Material circularity indicator (MCI) and the Longevity indicator. (Ellen Macarthur Foundation and Granta Design and Life, 2019) These indicators are time-based calculations, and by increasing the Time Horizon (TH), the uncertainties will increase due to technological changes. (Moraga et al., 2021) However, they can be useful as a decision-making guide for designers, but can also be used for several other purposes, including reporting internally, making purchasing decisions, and evaluating or rating organizations. (Ellen Macarthur Foundation and Granta Design and Life, 2019) P4 To define these indicators, this foundation introduces two cycles in a circular economy that products can experience, the Biological and Technical cycles. (Ellen MacArthur Foundation, 2019) The biological cycle refers to a cycle where organic materials/ products in the process of regeneration of natural systems return to bioeconomy, whereas technical cycles describe a cycle in which products, components, and materials are maintained in the marketplace at the maximum quality so long as possible by repairing and maintaining, reusing, refurbishing, remanufacturing, and ultimately recycling. (Ellen Macarthur Foundation and Granta Design and Life, 2019) (Figure 3) Moreover, the technical cycle in the circular economy is defined to have fully circular and fully linear material flows. (Figure 7)

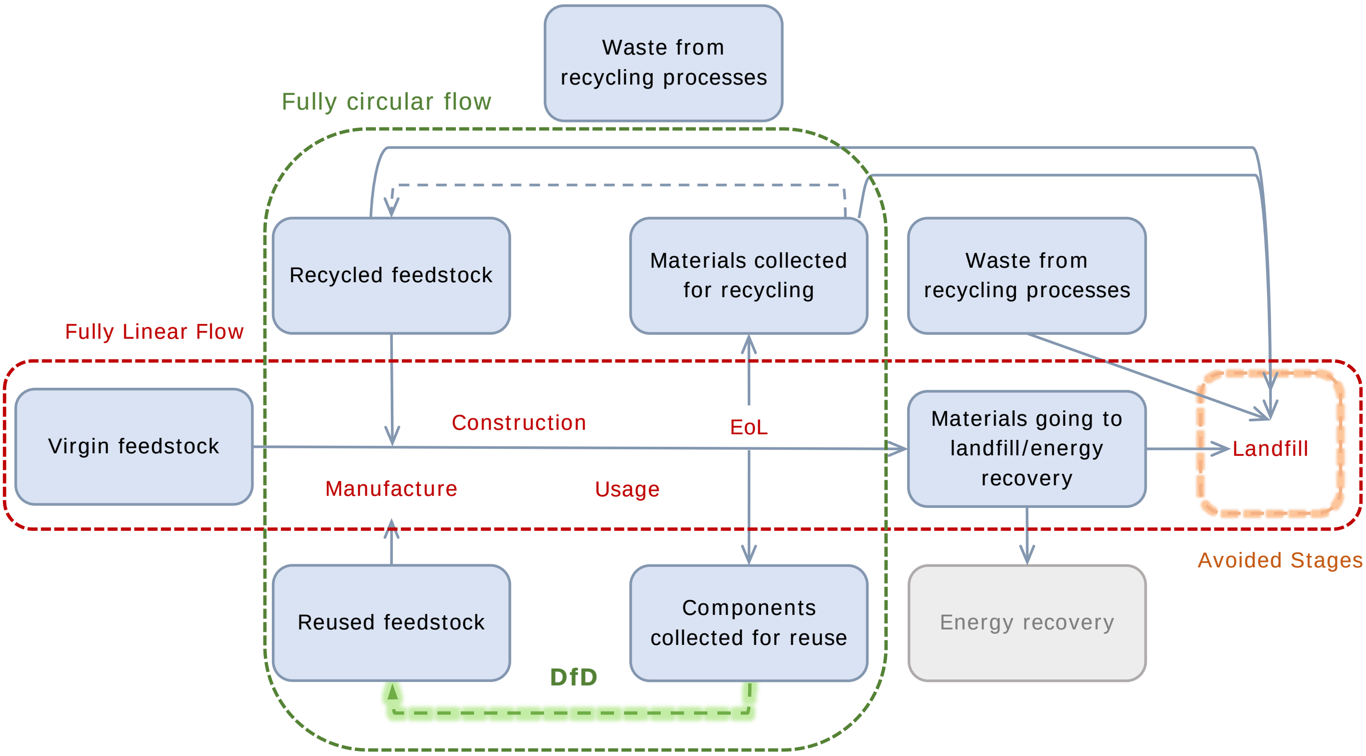


Figure 7 Technical cycle in Time-based CE indicators adapted (Ellen Macarthur Foundation and Granta Design and Life, 2019) and own assessment

Material circularity indicator (MCI):

Definition and aims: The material circularity indicator (MCI) of a product measures the extent to which the product's components minimize linear flow and maximize recirculating flow, as well as the length and intensity of use, compared to the average product in the industry. (Ellen Macarthur Foundation and Granta Design and Life, 2019) The MCI evaluates the ability to restore and regenerate material flows of a product/company and assesses the risks and impacts of that system. (Ellen Macarthur Foundation and Granta Design and Life, 2019) The MCI basis is obtaining biological materials from sustainable sources and ensuring that they remain uncontaminated and biologically available, and increasing the use of reused and recycled materials and reusing or recycling them for new cycles by increasing their lifetime and durability. (Ellen Macarthur Foundation and Granta Design and Life, 2019)

Calculations and results: In the MCI formula, the use of a long-term virgin product can have the same impact as the use of short-term reused or reusable products. (Ellen Macarthur Foundation and Granta Design and Life, 2019) The results of the MCI can be presented separately for each material or in the final index for the entire product, where the materials are weighted according to their contribution by mass. (Ellen Macarthur Foundation and Granta Design and Life, 2019) MCI=0 means that the flow is totally linear and MCI=1 refers to a fully circular flow, showing the efficiency percentage of that cycle by 0 or 100%. Because of users, stakeholders, product waste, dangerous products (REACH), and infrastructure availability for reuse and recycling, the planned design for circularity differs from the real-life implementation. (Ellen Macarthur Foundation and Granta Design and Life, 2019) Therefore, reaching 100% efficiency is not possible.

The MCI method uses the Utility Factor, which is the fraction of the duration and intensity of the use of products to their average in the market. (Ellen Macarthur Foundation and Granta Design and Life, 2019) Thus, the MCI for a product will decrease if the average becomes higher due to technology or improvements in the market. (Ellen Macarthur Foundation and Granta Design and Life, 2019) This leads to competitive situations where each product wants to be better than the market average to get a higher MCI.

Indicators: MCI illustrates the product's materials' circularity, although it does not include the materials themselves and the other impacts of these materials such as environmental impacts. Therefore, using complementary indicators to identify risks and impacts is recommended. (Ellen Macarthur Foundation and Granta Design and Life, 2019) Three complementary indicators can be used besides the MCI. They are 1. Complementary Risk Indicator, 2. Complementary Impact Indicator, 3. Profitability Indicator. (Ellen Macarthur Foundation and Granta Design and Life, 2019) Complementary risk indicators, such as measures of material scarcity and toxicity, indicate the urgency of implementing circular practices. (Ellen Macarthur Foundation and Granta Design and Life, 2019) Complementary impact indicators provide an indication of some of the advantages of circular models, including energy, water, and greenhouse gas impact measures, and perhaps biodiversity or soil loss measures in biological materials. (Ellen Macarthur Foundation and Granta Design and Life, 2019) Since the circular economy reflects also on the creation and retention of value from products and materials, this methodology also guides on assessing the profitability impact of moving to more circular business models. (Ellen Macarthur Foundation and Granta Design and Life, 2019)

EoL, DfD, and MCI: Regarding closed and open loops, MCI does not explicitly promote the closed loop over the open one. (Ellen Macarthur Foundation and Granta Design and Life, 2019) Closed loops, however, are necessary for component reuse and typically allow for purer material streams that increase recycling efficiency. (Ellen Macarthur Foundation and Granta Design and

Life, 2019) This means that, without the need for specific treatment in the methodology, the implementation of closed loops will result in higher MCI. (Ellen Macarthur Foundation and Granta Design and Life, 2019) Moreover, unrecoverable waste can be approached by 50:50 allocation between recyclable and recycled material waste in MCI calculations. (Ellen Macarthur Foundation and Granta Design and Life, 2019)

MCI is used to save costs and increase the revenue of production. (Ellen Macarthur Foundation and Granta Design and Life, 2019) To optimize the profitability of materials and save costs some actions can be taken. For example, the reuse of a product can reduce the complexity of the production and as a consequence, the emissions, material usage, and labor will decrease. Moreover, Reuse is more effective than recycling in terms of preserving more integrity of a material, embedded energy, and complexity of the process, Therefore, in MCI reuse is considered 100% efficient while recycling has a factor to add, and it does not consider the varying degrees of downcycling and upcycling, but only provides some guidelines as to which products can be considered recycled. (Ellen Macarthur Foundation and Granta Design and Life, 2019) In the case of reuse, more robust products can have a longer life span, and their lifetime can be increased even more with proper treatment during use or with designing that product for future disassembly and reuse in mind. (Ellen Macarthur Foundation and Granta Design and Life, 2019) These key drivers can be a good motive for producers to DfD.

One of the limitations of MCI is missing opportunities for material savings in a broader time frame than a single product cycle. (Moraga et al., 2021) Moreover, MCI assumes that the mass of the product will not change from manufacture to the end of use, which means that no part of the product is consumed during its use. (Ellen Macarthur Foundation and Granta Design and Life, 2019)

Longevity indicator:

Definition and aims: The longevity indicator is an eco-efficiency indicator that measures the length of time a resource is used (longevity), initially introduced by (Franklin-Johnson et al., 2016)Franklin-Johnson et al. (2016) and extended further by (Figge et al., 2018).

The longevity indicator provides a new performance measurement that evaluates the contribution to material conservation based on longevity. (Franklin-Johnson et al., 2016) According to the authors, this is a value-based approach rather than a burden-based one such as environmental impact assessment. (Figge et al., 2018) Longevity attempts to identify the extent to which a given system is circular. In other words, the degree to which the materials used in products last as long as possible within that system. A fully circular system is achieved when longevity is infinite. (Franklin-Johnson et al., 2016)

System boundary: The life cycle methodology consists of three generic components: initial lifetime, earned refurbished lifetime, and earned recycled lifetime. These components can be managed for making decisions and evaluating performance in the CE. (Franklin-Johnson et al., 2016)

Calculation and result: The longevity of a product's resources, from use to EoL, is a measure of the average length of product and material use. There is a minimum number of cycles in the calculation, but by further modeling of directional events, an infinite number of cycles can be included. (Franklin-Johnson et al., 2016)

In the extended method by (Figge et al., 2018), the longevity indicator is combined with an indicator that takes into account the first use, remanufacturing, and recycling into the same product to determine the number of uses of a resource. (Figge et al., 2018) In this method, a product system is considered which is this system that defines the scope of the indicators, rather than the resource itself, which could, for instance, be recycled beyond the product system. (Figge et al., 2018)

EoL, DfD, and Longevity: Longer use of a product, more recycling of a product, and more remanufacturing of a product are three key elements that help increase longevity. (Franklin-Johnson et al., 2016) For an organization that wants to increase the longevity of the materials of products, consumers should be encouraged to use products for longer periods of time, increase product returns, and choose the most effective recycling processes available for their products. (Figge et al., 2018) Beyond this application, the use of longevity as a decision support and performance assessment tool could be applied in several ways. For example, managers involved in the design of products and the determination of the value chain through which the materials used in a new product will pass could reasonably refer to longevity in order to make design decisions that enable the continued retention of materials and products. (Figge et al., 2018) Therefore, DfD can be decided by referring to increasing the longevity of products.

The longevity method is reliable, relevant to the organization, informative, simple to use, and applicable to a wide range of resources and products, and it is based on physical data, which guarantees a higher degree of validity. (Figge et al., 2018) It measures the time value of materials in use and reflects the decreasing rate of loss at each stage of the life cycle. (Figge et al., 2018) However, this method has some limitations. It does not take into account the complexity and resource consumption of remanufacturing and recycling. (Figge et al., 2018) The longevity indicator concentrates on the material use analysis from the perspective of one company and not from outside the company. (Moraga et al., 2021) It does not include losses due to the production process within the company or along the supply chain, nor does it include downcycling, although it does measure the time value of materials in use. (Moraga et al., 2021)

in-use occupation-based indicators: (URO/FRS)

Definition and aims: (Moraga et al., 2021) develop indicators for CE by assuming the in-use occupation time of products. Two indicators, the in-use occupation ratio (UOR) and the final retention in society (FRS), offer a way to assess the circularity of products by quantifying their in-use occupation. (Moraga et al., 2021) This means that materials are kept in a useful condition in products for as long as feasible, avoiding wastage or hibernation. (Moraga et al., 2021) These indicators focus on potential resources embedded in products, which may become secondary resources in a similar or different product. (Moraga et al., 2021) The challenge with circularity indicators is that simply adding up the mass of materials can provide misleading conclusions because materials do not share the same quality or price. (Moraga et al., 2021) Therefore, in-use occupation indicators do not consider the quality of the input materials in different cycles, to avoid the issue with different results due to defining quality factors based on the quality of materials' application and other factors. (Moraga et al., 2021)

Calculations: UOR is the performance rate of the total occupation for the use of the material during the Time Horizon (TH), and higher URO means that the analyzed material is more beneficial in society than a material with lower URO. (Moraga et al., 2021) FRS is the final material retention in society (%), showing the percentage of the primary raw material remaining in year 25. (Moraga et al., 2021) TH in both formulas is considered the period of the in-use phase because no benefits come from hibernation time. (Moraga et al., 2021) TH balances the need to predict how technology will evolve with the social responsibility to future generations, and uncertainties due to these technological changes will increase as the TH increases. (Moraga et al., 2021) In this respect, TH should be long enough to protect the future generations' interests, but short enough to reduce the temporal impact of technological change. (Moraga et al., 2021) In these indicators, the TH is considered 25 years.

System boundary: The phases described in URO are after the supply, in-use, and before hibernation phases. (Moraga et al., 2021) It starts with raw materials after their production, then the time during the materials' utilization, and ends with materials waiting for their EoL. (Moraga et al., 2021) Materials are more useful for a circular economy when they are in the use phase rather than in the supply and hibernating phase, so to achieve a higher URO, materials should remain in the supply and hibernating phase. (Moraga et al., 2021) The calculation of these phases includes the input masses of materials, the losses in all phases, and time. (Moraga et al., 2021)

EoL, DfD, and URO/FRS: After the hibernation phase, a product can also enter the use phase without having to go through the delivery phase, which DfD can be a proper example of that. In this way, CE strategies can be considered in a sequential arrangement by cascading the use of materials in products. (Moraga et al., 2021) The sequential use of raw materials in different product cycles can increase their utilization in use (for example, by repairing, refurbishing, and reusing the same product) or by recycling them to provide a secondary raw material in a closed or open loop.

In in-use occupation methods, reuse gets more credit than recycling. (Moraga et al., 2021) Although reuse can result in reduced losses, it may also result in shorter service life. (Moraga et al., 2021) Therefore, extending the reused material lifetime can be beneficial, and this can be possible by designing robust materials to be reused in the next cycles.

Urban mining Index (UMI)

Definition and aims: Urban mining index is a developed method for the objective assessment of the circular properties of building structures in the design of new buildings. (Rosen, 2022) Urban mining is the description of our cities, settlements, buildings, and goods as vast anthropogenic deposits of raw materials. (Rosen, 2022) Therefore, the Urban Mining Index was chosen as a name for this circularity evaluation method. The main goals of UMI are the connection of life cycles; having measurable quantitative parameters; identifying, analyzing, and defining appropriate evaluation levels; dismantling analysis; displaying recycling potential by quality; being simple to use and understand; applicability to building systems; and eligibility for certification schemes. (Rosen, 2022)

In addition, UMI attempts to be a practical planning tool to evaluate the specific circularity of construction projects, for example, to create urban mining concepts in the planning stage. (Rosen, 2022) UMI results indicate the ratio of circular materials as a fraction of the total amount of materials, the higher UMI results the higher the circularity ratio. (Rosen, 2022)

System boundary and calculation factors: UMI defines its system boundary into three phases: Pre-use, use, and post-use phases. Pre-use phase indicates the circulation of materials prior to their planned use, with the use, reuse, or recycling of available materials that have been extracted from the natural cycle, and the evaluation of the use of secondary and primary materials. (Rosen, 2022) The use phase covers the service life of the building and its components and takes into account the frequency of replacement. (Rosen, 2022) Post-use phase considers closing the loop after intended use and assesses the reusability of building components and materials. (Rosen, 2022) In these three phases, the UMI includes multiple material cycles, disassembly quality levels, possible end-of-life scenarios, material disposal costs, and disassembly effort in terms of time and energy. (Rosen, 2022)

EoL, DfD, and UMI: In principle, a quantitative evaluation of the recycling potential of buildings supports the industry's efforts to develop circular building products by creating a competitive situation with a corresponding demand. (Rosen, 2022) The UMI is, therefore, the first method for measuring the circularity rates of buildings that sufficiently accounts for the quality of subsequent use and the effort required to dismantle and separate recyclable materials by type at the end of their useful life. (Rosen, 2022)

UMI's approach toward EoL is quantifying the prediction of materials' EOL scenarios and the amount expected to be landfilled. (Rosen, 2022) UMI considers the reusability, recyclability, the ability to be downcycled, and energy recovery as the EOL besides landfilling, and it accounts for recycled and renewable material in the pre-use phase. (Rosen, 2022) for calculation of the circularity rate, it does not include non-renewable and landfilled materials. Therefore, it promotes the circular use of products, not linear flow, for which DfD can be an appropriate alternative. Moreover, by reducing the dismantling effort using DfD, the UMI percentage can increase, and this can show the implementation of DfD in UMI calculation can have benefits for the project.

Comparison of circularity evaluation methods

All mentioned circularity evaluation methods attempt to show the circularity and intensity of products’ consumption.

All of these four methods define their own system boundary. MCI, longevity, and UMI consider the life from prior to consumption to after consumption, while URO evaluates products after the supply, in-use, and before hibernation phases. MCI, longevity, and In-Use occupation indicators focus on a variety of products, while UMI is more concentrated on building circularity.

Regarding EoL scenarios and waste, MCI calculates the loss and durability during the use phase as landfill waste, and it does not include the production material loss, while URO/FRS includes loss for all stages in the calculations. Longevity includes the less loss rate during the product's lifetime stages, and UMI checks the percentage of different scenarios for EoL to account for the loss.

To check the relationship between DfD and Circularity evaluation methods, the approach of these methods toward reuse and reusability/ recycling should be discussed. MCI with a high rate of reuse/recycling can reach the highest target, 100% circularity, although it is not realistic. Longevity can increase by longer product consumption, recycling, and reuse of material. In URO/FRS reuse receives more credits than recycling, and while reuse can result in reduced losses, it can also result in a shorter life. Finally, UMI includes recycled and renewable materials in the pre-use phase and reusability, recyclability, down-cycling, energy recovery, and landfilling, although it will not account for landfilling and non-renewable sources in the calculations.

In general, all circularity indicators attempt to keep products in a circular flow and DfD, as a representative factor for designing for easy dismantling and reusing the materials, can get benefits.

2.3 Comparison of LCA- and CE- bases evaluation methods

It is necessary to clarify the relationship between sustainability and circularity, in a context where the transition to a circular economy is increasingly demanded. (Rigamonti & Mancini, 2021) Some studies such as (Haupt & Zschokke, 2017) and (Lonca et al., 2018) show that LCA and circularity do not reach the same conclusions about product environmental impact and circularity, while others claim otherwise, for example (Schmidt et al., 2020) and (Stanchev et al., 2020) mentioned. (Rigamonti & Mancini, 2021) Therefore, the difference between the conclusions can be an indication of the importance of the comparison between the LCA-based and Circularity evaluation indicators, however, these studies are not carried out on the buildings.

The LCA methodology is not well suited to assess the degree of circularity of the studied system, as the LCA models are based on a more linear material flow framework and the LCA indicators do not take into account the available anthropogenic deposits. (Rigamonti & Mancini, 2021) On the other hand, the strength of LCA is its goal of avoiding load shifting, while circularity metrics are unable to achieve the same because they focus on only a few goals or a particular activity. (Rigamonti & Mancini, 2021) Moreover, the circularity indicators which are based on Material flow analysis (MFA), cannot fully inform about the sustainability of a product, (Rigamonti & Mancini, 2021) because the circular economy is often characterized as a mixture of reducing, reusing, and recycling, with little emphasis on the need for a system transformation or the link between the circular economy and sustainable development. (Kirchherr et al., 2017)

LCA analysis has some limitations, for example, the results calculated by LCA analysis are difficult to generalize due to specific geographical data sets and different reliability rates. In addition, LCA analysis is usually simplified to be less time-consuming, which may not be realistic, although the results are essential for decision-makers, and the decision-making efficiency may be reduced by the overabundance of environmental indicators. (Cottafava & Ritzen, 2021)

Another issue is comparing the LCA methods with different allocations. For instance, evaluation of the environmental benefits of selecting reused components in a new building, and design with upstream or downstream reuse incentives will produce different results that cannot be reliably compared, combined, and predicted. (De Wolf et al., 2020) Current LCA methodologies are not yet adapted to the practice of reuse and its benefits and burdens, and to promote a shift to circular cities, it is necessary to resolve differences in the results for reused components from one methodology to another. (Adriana Del Borghi, Luca Moreschi, 2020)

According to (Korhonen et al., 2018), circularity limitations can be divided into six categories: thermodynamic and system boundary limits, limits set by the physical scale of the economy, limits set by path dependency and lock-in, limits imposed by governance and management, limits imposed by social and cultural definitions. For instance, one of the issues with system boundaries is that the burdens can shift during cycles, or the concept of waste is dependent on the social and culture of a society, and changing it to reuse the materials, can be challenging. (Korhonen et al., 2018)

Despite these limitations, LCA is one of the most widely used methods for evaluating CE, as shown by the results of the reviews by (Corona et al., 2019) and (Sassanelli et al., 2019). LCA is used to compare and choose among different CE strategies, and it provides an understanding and assessment of whether and to what extent the environmental benefits claimed by CE strategies can be achieved. (Corona et al., 2019; Rigamonti & Mancini, 2021)

On the other hand, [35] states that no authors have come to the conclusion that circularity indicators alone can be used for the selection of the best alternative in a circular economy project because these indicators are only a partial representation of the environmental characteristics of a system. In contrast, circularity metrics seem to be easier to convey, and a high level of circularity can help build good relationships with customers, enhance reputation among stakeholders, and facilitate access to finance. [35] Therefore, including both LCA and circularity measurement in the assessment of circular economy strategies at an earlier stage of product concept provides an insight into how environmental sustainability aspects can be integrated into circular economy strategies. [35]

Aim of this study: This study will try to imply the chosen methods of LCA-based and circularity evaluation methods on different options of a project including DfD. The differences and similarities of LCA-based and CE evaluation methods, the different perspectives about the reliability of each method, and the lack of evaluating GHG reduction by DfD project indicated by these methods reveal an evident need to develop a study to test different methods on a DfD case.

3 Research goals and questions

In order to develop a study to test different methods on a DfD case, the first step should be to select the methods to be tested. Then, the case study with DfD options should be defined to present different alternatives for future comparisons. Finally, the methods with the chosen allocations for circular material flow should evaluate the different scenarios for the final conclusion.

Therefore, this master thesis aims to find the relationship between LCA methods and CE indicators and designing for disassembly. This study will assess this relationship by evaluating a case study with chosen methods. The following questions are defined to reach this goal.

Research questions:

- What is the relationship between LCA-based methods Circularity evaluation methods and DfD?
- Design for disassembly - do life cycle assessment and circularity indicators show the benefits?
- What are the differences between these methods regarding DfD options? Which one of these methods can show the DfD’s effect?
- Which one of the prefabricated DfD options, the modular or panelized design, is better regarding circularity and GWP emissions?

The following sections will explain the scope of the study, the methods chosen and the basis for their selection, the case study, and its alternatives. The results of the evaluations are then presented and interpreted to draw conclusions about the association between the methods and DfD.

4 Scope and Methodology

This study aims to determine the impact of the design for disassembly on the results of LCA methods life cycle assessment and circularity indicators. Moreover, for promoting DfD in the construction industry some measurements can be used to quantify the positive impact of DfD on reducing CO2 emissions. Circularity indicators try to measure circularity potential, while LCA calculates emissions over the life cycle. By comparing the results of the two approaches, it is possible to identify synergies and trade-offs between the two objectives of reducing greenhouse gas emissions and maximizing circularity.

First, after reviewing different methods of LCA and methods of circular economy indicators, NS3720, Futurebuilt zero, and Urban Mining Index were chosen for application in the use case. NS3720 and Futurebuilt zero were chosen because they are based on EN15978 and EN 15804, therefore, they could cover most of the aspects of these standards. Moreover, Futurebuilt incentivizes reuse and reusability in the calculations, which is relevant to DfD calculations, while there is no value assigned for them in NS3720. Therefore, it was interesting to see the difference between the results based on the reuse and reusability allocations. Regarding Circularity indicators, the UMI was chosen because it was developed based on building sectors including the disassembly and value factors, which are relevant to DfD besides the reuse and reusability of components.

Second, a module in the “Treet” building in Bergen, Norway, was chosen as a case study. This building was chosen because it was designed with prefabricated modules which can be assumed that they can be dismantled to be reused. The results of all 3 calculation methods were tested on different versions of this case study.

In the next sections, the methodology of chosen calculation methods, their scope, the case study, the case study’s considered versions, and the used tools for each purpose will be explained.

4.1 Case study and data collection

The “Treet” in Bergen, Norway, is a 14-story residential building built in 2014-15. (ARTEC, 2018) This building was the world's highest building with a wooden structure until 2018 when the Mjøstårnet building was surpassed by. (ARTEC, 2018) The building has been built with load-carrying glulam trusses built by Moelven Limtre supplier as the main structure. (Malo et al., 2016) Two levels 5 and 10 were chosen to include an extra concrete layer on the floor to strengthen levels in the structure. Kodumaja manufacturer located in Estonia built the designed prefabricated modules and shipped them to Bergen to be assembled. (Malo et al., 2016) This building includes 62 apartments with a net area of 5830 m^2 and was built under SWECO’s supervision.

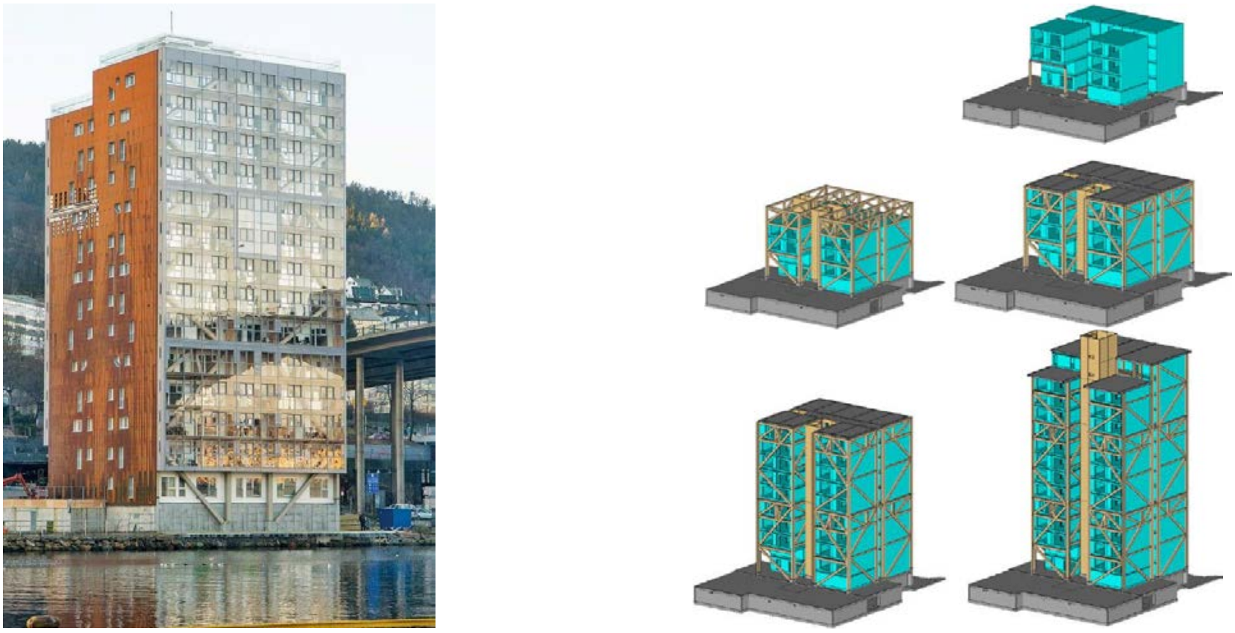


Figure 8 Treet building and construction phases, Images source: (Malo et al.,

Kodumaja modules are prefabricated modules made in Estonia that have timber frame structures on the floors, roofs, and walls. (SINTEF Building and Infrastructure, 2015) These modules contain all the doors, windows, internal and external cladding, and technical installations. (SINTEF Building and Infrastructure, 2015) These modules do not include any dangerous substances based on EC Guidance Paper H and the EU database. (SINTEF Building and Infrastructure, 2015)

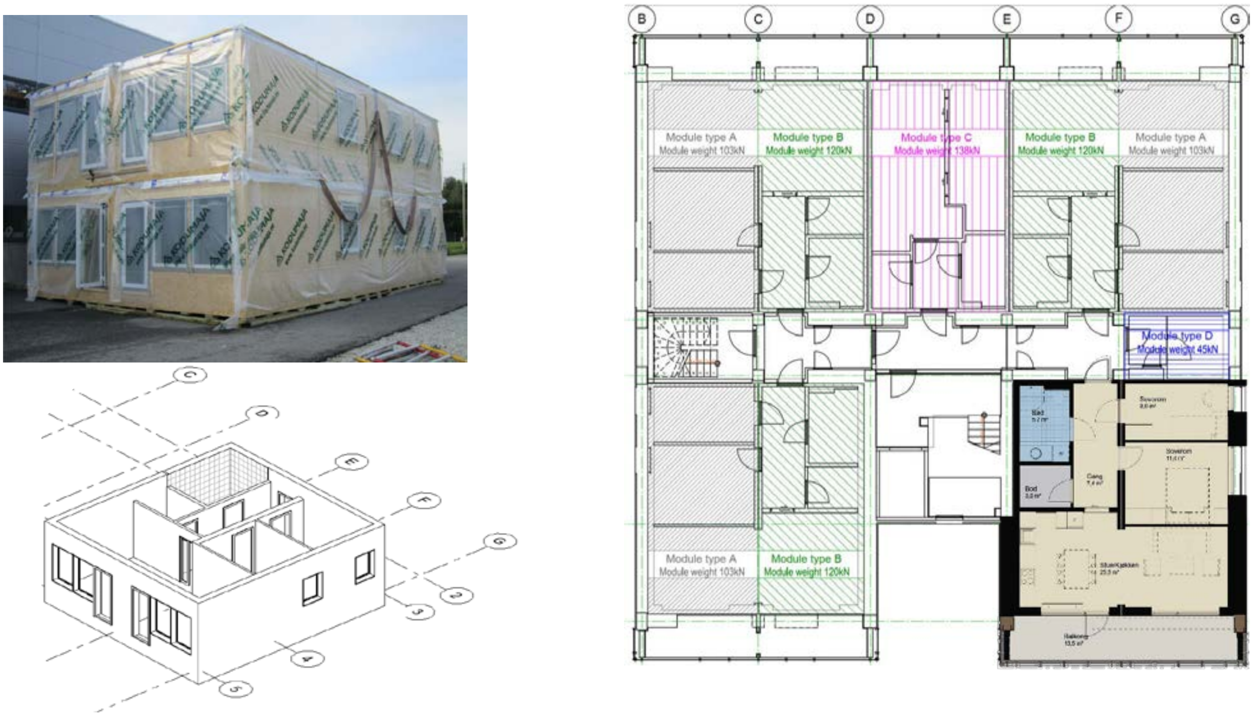


Figure 9 Kodumaja's prefabricated modules and plan, image source: (Malo et al., 2016), own drawing in Revit

For testing the impact of Design for Disassembly on LCA and Circularity evaluations, one of these prefabricated modules was assigned to be the case study. To assess the influence of DfD on the methods, some assumptions are made, for example, the service life of some materials has been changed to fit the idea that these modules are designed to be reused, and therefore they are more resilient. An attempt is made to make these assumptions more realistic based on available data and documentation. Although it is questionable how realistic it is to predict the EoL of a module after the first cycle and then after two cycles, the results for comparison of the options can be reliable. Figure 10 explains the option in general, and in the next paragraphs, the details of each studied option are explained.

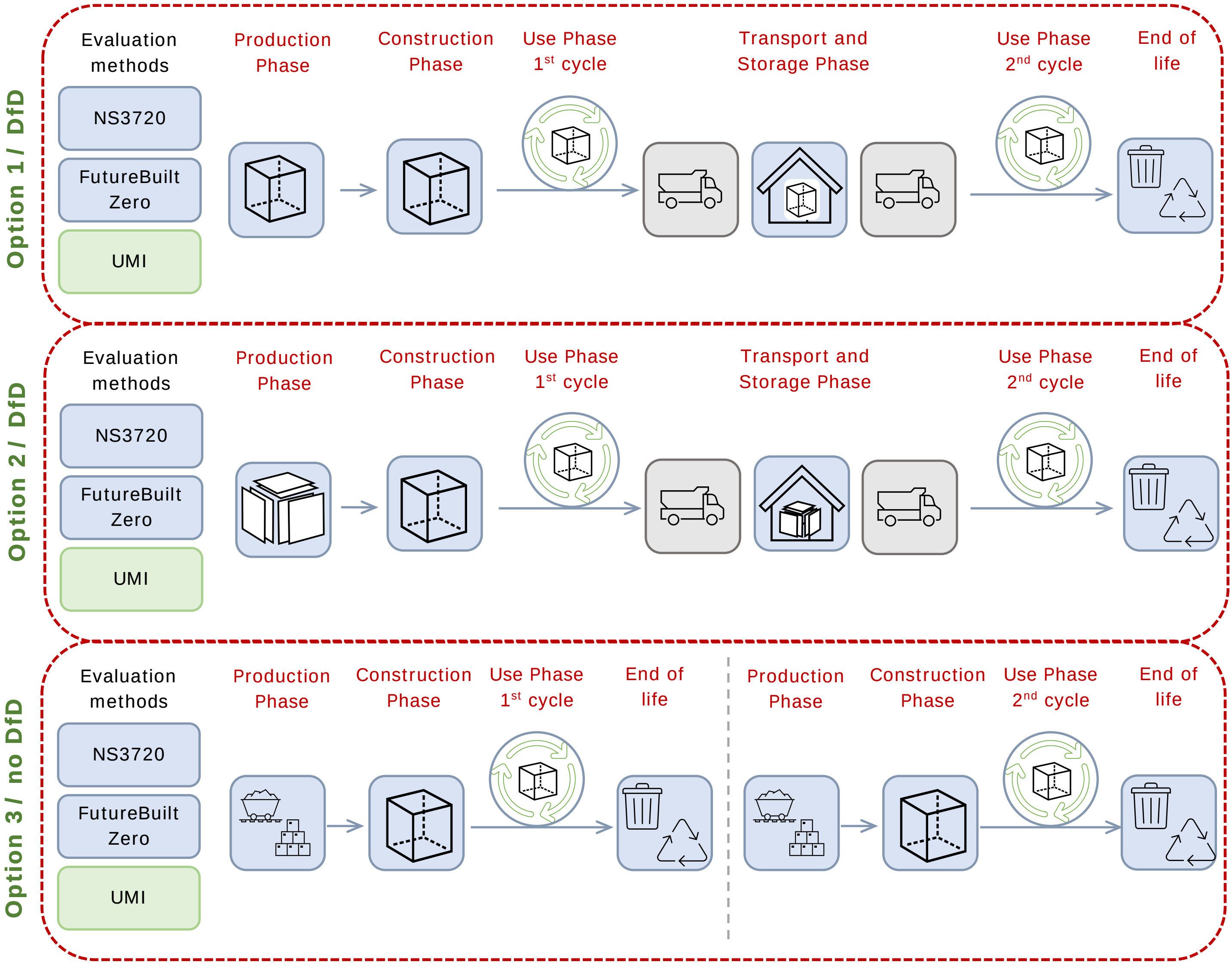


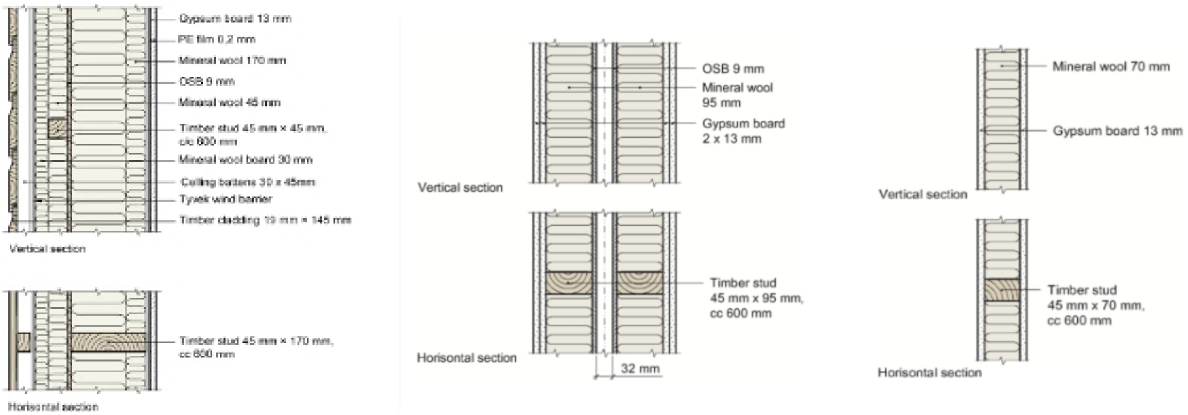
Figure 10 Model of studied options, and their suggested lifecycles

Some assumptions were made for simplification and better comparison. First, it was assumed that these modules are designed for disassembly, and after being shipped from Estonia to Bergen, they would be assembled on-site without any waste on site. Then after 60 years (one life cycle), they would be disassembled and stored in Norway to be built again in Bergen for another 60 years of life. In the end, they will be demolished. (Option 1)

The next option (Option 2) has the same assumptions in both cycles as Option 1, except that the prefabricated walls and floors would be shipped to Bergen and assembled there instead of full modules. In this case, to construct one apartment only one wall/floor is needed between the adjacent apartments.

The last option (Option 3) was assumed to be the usual on-site construction in Bergen, where all materials would be transported to the site and the module would be constructed in separated two cycles. At the end of each cycle, the materials would reach their end-of-life scenario.

For analyzing these options, one module with construction details was modeled in Revit. The detailed information about the walls/floors was derived from the Sintef report, (SINTEF Building and Infrastructure, 2015) and the plan was based on one of the non-structural levels from the Treetsameie website. (Snølys.no, 2015) Figure 11 illustrates these construction details, and Appendix 2 will show the information about the construction materials used in the calculations. After modeling one sample unit, detailed information about the area and thickness of each material was collected with the Material take-off feature in Revit. Then an Excel sheet containing the mass, area, thickness, Volume, and Mass/kg was made to be used in further calculations.



Standard wall

Principle design of standard external walls.

Principle design of standard separating wall between modules and between housing units.

Principle design of standard internal walls.
Stud dimension is 45 mm x 95 mm in loadbearing walls.
Shaft walls EI 30 have single layers of gypsum board on each side as shown, shaft walls EI 60 have double layers on each side or an additional 15 mm gypsum board type F on the shaft side.

Principle design of separating floor construction between modules. Solid wood joists.
The lowest part is the roof/ceiling structure of the bottom module, and the top part is the floor structure of the top module.

Principle design of suspended ground floor construction in bathrooms.

Figure 11 Construction details of prefabricated modules, (SINTEF Building and Infrastructure, 2015)

4.2 Calculation methods and used software

The evaluation methods used in this study are NS3720, FutureBuilt Zero, and UMI. For LCA-based calculations, the Reduzer program is used and then for getting two cycles all the information and result were combined in Excel. For the evaluation of UMI, Excel spreadsheets were created for the calculations. The digital format of the calculations in Excel sheets is attached to this thesis in Appendix 3.

LCA methodologies: NS3720 and Futurebuilt Zero

For calculating LCA, a system boundary was set to determine the scope of this analysis. The Functional unit for life cycle analysis is chosen to be $1m^2$ of the gross floor area of one Treet building's prefabricate module. The module's lifetime based on Kodumaja is 50 years and requires maintenance. (SINTEF Building and Infrastructure, 2015) However, In the two studies from Denmark and Norway, "Estimation of the Service Life of Residential Buildings, and Building Components", and "Levetider af bygningsdele ved vurdering af bæredygtighed og totaløkonomi" (Niels-Jørgen Aagaard, Erik Brandt, Søren Aggerholm, 2013) (Bohne et al., 2006) it is shown that the average service life of a residential building can be 120 and 126±43 respectively. Therefore, in this thesis Reference service life was considered as two cycles with 60 years each.

For calculating LCA with two chosen methods, Reduzer was used as a tool for calculations. Reduzer is a newly developed software that can be used to calculate the environmental footprint of construction projects to reduce emissions for the construction industry. (The research council of Norway, 2022) First, components were made in Reduzer by choosing EPDs for materials in each component. Then, the three options were made as a sample project in Reduzer, (Figure 10) and the GWP results were taken out as a spreadsheet. Then, the second cycle was calculated based on the GWP results of each stage and some assumptions in Excel that will be explained in the following sections.

As mentioned before, the LCA included the following life cycle stages, as defined in the NS3720 and Futurebuilt Zero: A1-A5, B1-B7/8, C1-C4, and D. However, this study accounted for A1-A5, B1, B4, C2, and C3 stages in NS3720 and A1-A5, B1, B4, C3, and D stages for Futurebuilt Zero. The reason for this choice was the provided results by Reduzer, the relevancy to the project, and the shortage of time to cover all stages.

In the LCA, the pollution pays and modularity principle was considered because it was the basis of both methods. (Norsk Standard, 2019) These allocations explain that all environmental impacts and waste generated should be reported at the life cycle stage where they occur. (Norsk Standard, 2019) Therefore, the following stages are calculated accordingly:

Module A1-A3:

A1-A3 is the production stage. In the first cycle, this stage for the prefabricated modules and panelized walls/floors (options 1 and 2) included the raw material supply, transport to the Kodumaja, and the assembly of materials there. On the other hand, in the on-site construction version (Option 3) this stage did not include the assembly part.

In the next cycle, due to the reuse of all prefabricated modules and walls/floors in O1 and O2, the A1-A3 did not have emissions unless there was a replacement of some materials at the end of the first cycle. In this case, the A1-A3 was equal to the production of replacement materials. Whereas, in the O3, the raw materials were assumed to be produced again.

Moreover, the amount of material used in the three options was different. O1 had the most amount of material because all prefabricated modules to build the building contained all walls, almost all the floors, and roofs. However, in O2 and O3, only one wall and one floor between two modules were required to shape the final building. Therefore, in this thesis, based on Sintef's details (SINTEF Building and Infrastructure, 2015), the emissions of the internal wall thickness= 29.2 cm and the internal wall thickness= 32.2cm for wet areas were considered half between two vacant modules, and the emissions of the ceiling for wet areas have not been included in order not to be counted twice. Therefore, less material was accounted for the O2 and O3 than O1. Appendix 2 shows the details of the walls.

Module A4:

A4 accounts for transport from the production place to the construction site. For the first cycle, the production of each material was based on its EPD. In the O1 and O2, A4 included the transfer of materials from their production origin to Kodumaja, Estonia, then the assembled result was transferred to Bergen to build Treet. On the other hand, O3 only had the production to the building site. In this regard, two versions were calculated to see the effect of transport on the results: 1. Prefabrication company in Norway 2. Prefabrication company in Estonia (Kodumaja).

For the next cycle, it was assumed that there was a storage facility in Norway and the reusable components and modules would be transported there to be used again on the same site. Therefore, the transport included the distance from the site to the storage and from the storage to the site.

To regulate the transport distance, a more simplified range of distances was chosen for this purpose. This simplification was based on adopting the actual distance to Reduzer's simplified version of transport systems and adding a few more options. The calculations do not include truck transportation from the port to the site for modules transported by ship, because the site is located in a place where there is direct access to the ships. Table 1 depicts these considerations.

Table 1 Transport-adapted distances for calculations

From	To	Distance (km)	Means of transport
Germany	Estonia	1500	Truck*
Austria	Estonia	1000	Truck
Denmark	Estonia	500	Ship**
Norway	Estonia	2000	Ship
Luxembourg	Estonia	1500	Truck
Sweden	Estonia	500	Ship
Finland	Estonia	200	Ship
Poland	Estonia	1000	Truck
Germany	Norway	500	Ship
Austria	Norway	2000	Truck
Denmark	Norway	500	Ship
Sweden	Norway	1000	Truck
Finland	Norway	1500	Truck
Poland	Norway	2000	Truck

* Truck accounts for 1.667kgCO2e/kg km emissions in Reduzer.
** Ship accounts for 0.03 kgCO2e/tkm emissions in Reduzer.

Module A5:

A5 provides a basis for site selection for development purposes and can be used to report the GHG emissions associated with the development of a site as part of the overall GHG emissions for the construction. (Standard Norge, 2018) Here, A5 resulted from the Reduzer calculation including only the incineration wastage of used materials, product wastage, and transport wastage during the construction. In the first two options, because of designing for a disassembly nature, no waste was assumed during the construction site in both cycles. However, as it is calculated for 5% waste in Futurebuilt Zero, (Andresen et al., 2021) a variation for O2 was calculated with accounting for 5% waste. However, the O3 version due to the on-site construction, would have 10-15% waste which was the default assigned in Reduzer.

Module B1:

B1 was included in the Futurebuilt Zero result, representing biogenic carbon uptake and cement carbonation in the “use phase” of the building. The negative emissions of biogenic carbon uptake by wood materials have two reasons. First, new trees grow in the same area where they were harvested, resulting in carbon uptake, and this carbon uptake takes place during the use phase of the building. (Resch et al., 2021) Second, some of the carbon stored in the wood products will be oxidized and returned to the atmosphere at the end of their life. (Resch et al., 2021) Due to the high wood mass in the module and some concrete surfaces on the floor/roof, B1 in Futurebuilt zero can have a positive impact on the results, by reducing the total emissions level.

In NS3720, biogenic carbon occurs before harvesting the wood materials, and both uptake and emissions are accounted for in the GWP. (Standard Norge, 2018) Therefore, biogenic carbon does not influence the GWO in NS3720. This standard assigned biogenic carbon uptake to A1 and gives incentives for using wood as a raw material, and emissions to C3-C4. (Standard Norge, 2018) B1 in NS3720 calculates only cement carbonation and not biogenic carbon uptake. (Standard Norge, 2018)

Module B4:

In the lifetime of the module, some elements had to be replaced completely and they should be calculated in module B4. Based on EPDs, the moisture membrane in the bathroom is required to be replaced every 30 years. In addition, the ceramic should be replaced every 25 years based on the assigned EPD, although (Souza et al., 2018) suggested replacing the ceramic by 48 years, and therefore a 30-year life was considered for the ceramic to be replaced with the membrane. Therefore, the ceramic, the mortar for ceramic, and the membrane in the bathroom were assumed to be replaced every other 30 years, 3 replacements during two cycles. These materials, therefore, would cause A1-A3 emissions for the second cycle besides their B4 emissions. Moreover, windows should be replaced every other 40 years, 2 replacements for 120 years. The emissions for production to the end of life of windows were included in the B4. Figure 12 shows this replacement on a diagram.

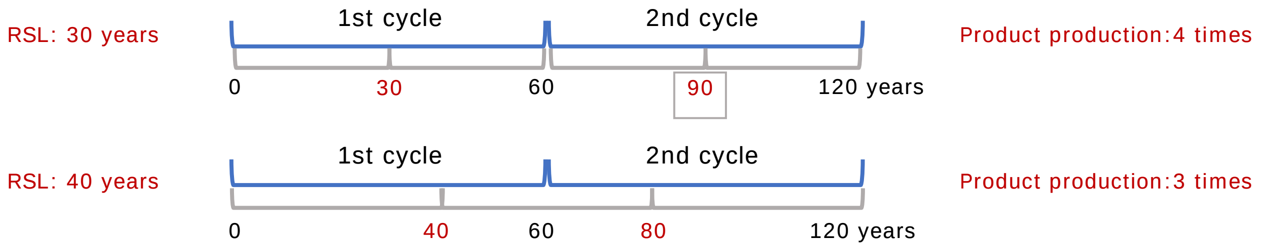


Figure 12 Component replacement diagram

Module C:

Module C represents the end-of-life stages, and Module C2 is assigned to the transport of demolished components to waste processing, and it is considered 50 km in Reduzer for the second cycle. C2 in the first cycle for O1 and O2 accounted for the transporting module and panelized components to the storage in Norway, and in O3 it referred to the transporting of waste. In module C3, the incineration waste from the waste process was accounted for. In the first cycle, C3 was assumed zero in O1 and O2, because it was assumed that all the materials would be reused for the second cycle, and the waste processing would be accounted for in the next cycle. Whereas option 3 would have the emissions from C3 for waste processing in both cycles.

Module D:

Module D expresses the benefits and loads of reusing, recovering, and recycling material. And it is beyond the first cycle's system boundary. Therefore, module D was counted in the second cycle. The reason for this was that the materials were assumed to be reused completely, therefore, they did not have any end-of-life and the benefits beyond the system boundary went to the next cycle. (Rasmussen et al., 2019) Figure 13 depicts graphically the 100:0 allocations of emissions between the cycles.

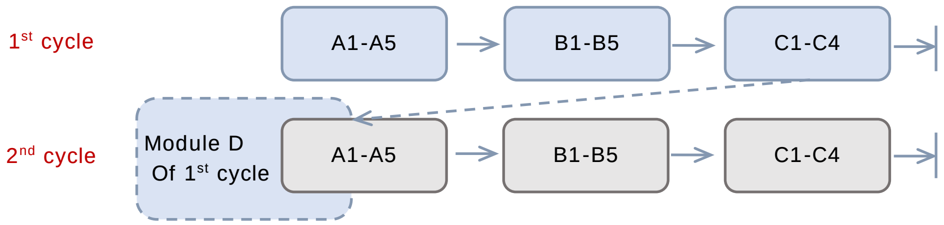


Figure 13 Principle of 100:0 allocation in two cycles adapted from (Rasmussen et al., 2019)

Since emissions are calculated for the incineration of all combustible/organic waste for which there is no evidence of reuse (facilitation for reuse), energy recovery is not included as a factor for DfD in the master's thesis. Over the next few years, there will be an increase in the proportion of materials that will be recycled as a result of the circular economy requirements, and therefore a decrease in the proportion of materials that will be incinerated. (Resch et al., 2021) The assumption is that there will be a linear reduction from 100% (2020) to 20% (2080) and then a constant reduction. (Resch et al., 2021)Thus, when the DfD considers reusability, it cannot be transformed into waste for incineration.

Inventory system boundary

The inventory from modules of the Treet building included one apartment's external and internal walls, doors and windows, floor, and ceiling. The technical systems, attached furniture, external work like balconies, and the main building structure were not included. The details of this inventory originated from Sintef's report about Kodumaja's modules, (SINTEF Building and Infrastructure, 2015) although the assigned EPDs were based on their relevance to the component and their moderate emissions compared to other products, chosen from the Reduzer database. (The research council of Norway, 2022)

Circularity indicators: UMI and used calculation

The urban mining index method was chosen because this method contains some factors such as the work factor that are relevant when talking about dismantling elements in DfD and it is designed to evaluate buildings.

The UMI method was developed in Germany and some adaptations were required to get more accurate results in the Norwegian context. Therefore, the adaptations made by Andrés Salazar in his Master thesis, besides Dr. Anja's Rosen Ph.D. dissertation document, were used in this thesis. (Rosen, 2022), (Salazar, 2022) The UMI calculation factors and these adaptations to Norway are explained in the next paragraphs.

Certified or not certified materials

In UMI calculations, materials are divided into certified and non-certified categories. These categorizations are based on the material's dismantling potential, which should have been found in EPDs. Certified materials are those which can be dismantled by type and do not contain hazardous substances. However, some materials can have both certified and non-certified fractions. In this thesis, all materials were assumed to be certified ones so that they could be reused again which was the basis of DfD.

The information about the materials comes from the book “Manual of recycling: buildings as sources of materials” (Hillebrandt et al., 2019) and some calculations based on the EPDs. For instance, the material composition of windows and doors was calculated by the table in the EPDs illustrating the products’ specifications, and these calculations are presented in Appendix 4.

Selective dismantling (SD) or/and usual demolition (UD)

These certified and non-certified materials gain importance when it comes to dismantling processes. This process can be done with selective dismantling (SD) and usual demolition (UD) according to UMI. Selective Dismantling (SD) requires machinery and skilled workers to dismantle and sort materials by type. Thus, the component with certified material can be easily sorted in the SD category. Whereas the UD will not include careful dismantling, the process of sorting materials will be very difficult, and the potential of material recycling will be low. Therefore, in this thesis selective dismantling was chosen for O1 and O2 which included DfD, because DfD’s base is to design the components in a way that they can be dismantled and sorted for future use.

End-of-life scenarios and Norway waste treatment

Considering more cycles than one for one product lifetime requires the categorization of end-of-life scenarios. In UMI 4 categories are mentioned for EOL: Reuse, Recycling, downcycling, and energy recovery. Every material can have one or more of these scenarios based on its properties and dismantling quality level. These scenarios were presented in Dr. Rosen’s dissertation according to the German Commercial Waste Ordinance. Therefore, for using these scenarios in Norway, some adaptations are needed. The adaptations made by Andrés Salazar in his master’s thesis were used to determine the EOL scenarios for the materials in this study. The most possible EOL of materials is energy recovery by incineration in Norway, (Statistics Norway, 2022) although some changes in the tax and technology can change this EOL scenario to a more environmentally friendly option like reuse or recycling. Table 2, showing the adjusted chart of EOL scenarios, was used in UMI's final calculations for this study. (Salazar, 2022)

Table 2 EoL scenarios adjusted to Norway adapted from (Salazar, 2022)

Material	Reuse	Recycling	Downcycling	Energy Recovery	Disposal and non-certified
Concrete		🔵	⚪		🟢
Brick	🟠		🔵 ⚪		🟢
Ceramic			🔵 ⚪		🟢
Wood	🟠		🔵 ⚪	🟢	
Biological		🔵 🟢		⚪	
Glass		🔵 🟢			⚪
Plastics		🔵 ⚪		🟢	
Sorted Metal	🟠	🔵 🟢			
Gypsum		🔵 🟢			⚪

🔵Highest quality
🟢Most probably
⚪Second most probably
🟠Reusing

Material recycling content, Material loop potential, and Material End of Life

Materials have another type of properties that is important to evaluate, in addition to the certified and non-certified content explained before. The mass composition of recycled content, renewable primary resources, and non-renewable primary resources in a material is considered Material Recycled Content (MRC). (Rosen, 2022) This should be applied for both pre-use and post-use cycles for UMI calculations.

The next feature of materials is the Material Loop Potential (MLP), which reports the percentage of recycled content from the recycled secondary raw material and the maximum possible recycled content in the production of used components. (Hillebrandt et al., 2019) In addition, Material End of Life (MEoL) is one of the material properties that should be counted when examining what is the possible content that can undergo multiple cycles without material loss. MEoL provides the amount of potential waste or utilization that can be generated when the material is dismantled after the first cycle.(Hillebrandt et al., 2019) All these MRC, MLP, and MEoL can be found in the Manual of Recycling book, and they are based on different EPDs, industry association trials, industry supplier documents, and government statistics.(Hillebrandt et al., 2019) The assigned MLP, SD, and UD are presented in appendix 5.

Cycles and loops in UMI

UMI explains how much material can go through future cycles and avoid being landfill waste. Thus, the UMI uses two cycles, the pre-use and post-use cycles. Pre-use cycle refers to the period when materials are selected to be a part of a project, while post-use is the period starting after the first cycle decided by the end-of-life scenarios. The pre-use cycle shows the mass fraction of materials of their origin, recycled content, renewable primary resources, and non-renewable primary resources, and it concerns the materials that are going to be installed in a new building. Whereas the post-use cycle displays the mass fraction of materials by their possible EoL scenario. These fractions are illustrated in Appendix 3, the excel files.

Moreover, the two cycles can have a Closed Loop Potential (CLP) or Loop Potential (LP). Closed loop potential is for the materials which are certified and loop potential can have both non-certified and certified content. The value of pre- and post-use are considered equal in the calculations of UMI, and each of them gets half of the value. By accounting for DfD and using certified materials, the CLP was calculated for the three options. Therefore, first, the CLP of each cycle was calculated for use in the UMI evaluation.

Dismantling effort, work factor (Fw)

The quantifying dismantling effort for comparison reasons was a complex but necessary task for the description of the complexity of dismantling activity that can have positive or negative effects on the circularity potential rate. Dr. Anja Rosen came up with a new benchmarking system for the complexity of dismantling materials which is divided into 5 groups from very low to very high effort rate. (Rosen, 2022) Table **3** shows the FW rate (Rosen, 2022) The Fw is closer to 1, it is easier to dismantle.

Table 3 Work Factor (FW) assessment adapted from (Rosen, 2022), (Salazar, 2022)

Work W (MJ/m2)	Evaluation	Work Factor (Fw)
< 1 Quintile	Very low (sehr gering)	1,00
< 2 Quintile	Low (gering)	0,90
< 3 Quintile	Medium (mittel)	0,80
< 4 Quintile	High (hoch)	0,70
> 4 Quintile	Very high (sehr hoch)	0,60

This study used the same factors as the main UMI, without adjusting it to Norway, due to the complexity of calculations and shortage of time. Moreover, the most important parameters are time, resource usage, and process type, and it does not include economic values. Therefore, it is not a wrong assumption to keep the same evaluation for the work factor in Norway.

DfD's purpose is that the components can be dismantled in the EoL easily. For that reason, it is assumed that Fw for DfD would be closer to 1. In the O1, in which the modules would be stored as they were, the work factor was considered 1,00 (very low effort), and in the O2, where the panels were designed to be dismantled, the 0.90 (low effort) was assigned to. On the other hand, for the usual dismantling process, work factors depended on the materials themselves. This information came from Dr. Rosen's thesis and some assumptions if there were not the same material dismantling effort rate.

Cost/revenue from materials (value factor, Fv) and Norwegian market

This factor describes the expense or income of disposing of the various construction wastes at the end of the life cycle. Fv value depends on the cost of waste collection for processing. When the FV value is 1, it means that the recycling companies will not charge for taking the waste. If the value is more than 1, it will refer to gaining revenue for waste, while a value less than 1 represents more costs for waste treatment. A more value factor has a more positive effect on the UMI results, in other words, high Fv leads to a higher circularity potential rate. This factor was adopted from Dr. Rosen's dissertation and adjusted to Norway's economic rates by Andrés Salazar. The Fv factor based on waste with some examples of waste handling costs in Norway is presented in Table 4.

Table 4 Value Factor (Fv) assessment adapted from (Salazar, 2022)

Price NOK	Evaluation	Factor Value (Fv)
> 57.500	Extremely positive	1,3
57.500	Very positive	1,2
30.500	Positive	1,1
11.000	Slightly positive	1
-1.200	Slightly negative	0,9
-1.285	Negative	0,8
-1.737	Very negative	0,7
< -1.737	Extremely negative	0,6

This study used the adjusted Fv version and Appendix 5 shows a few examples of the Fw and Fv used in this study.

The calculation method and data collection

For calculating UMI, more information about the used material in each component was needed, besides the explained information. Therefore, the material combination and thicknesses were assigned to the modules from Sintef's report, the density came from EPDs, and the areas from the Revit material take-off feature.

After collecting all the needed information in an Excel file, the mass compositions were changed from percentage to Kg. Then, the CLP pre-use was calculated based on formula 1.

Formula 1: $CLP_{pre\text{-}use} = RC + RW + RWCR$

Where,
RC= Recycled certified material, RW= New non- Certified renewable, RWCR= New Certified renewable

For calculating CLP pre-use, the primary masses were divided into their respective end-of-life scenarios according to formulas 2 and 3.

If SD= rc and UD=d/nc,
Formula 2: Then rc mass composition (Kg)= Total Mass (Kg)* MLP * Fv * Fw,
Formula 3: And d/nc, mass composition (Kg)= Total Mass (Kg)- rc mass composition (Kg)
And the other compositions will be 0 kg.

After converting all the material composition data of the post-used cycle, the CLP post-use was calculated according to formula 4.

Formula 4: $CLP_{post\text{-}use} = RU + RC + DCCR + ENCR$

Where,
RU=Reusing, RC= Recycling, DCCR= Downcycling certified, ENCR= Energy recovery certified

UMI was calculated by adding 50% of each CLP, based on formula 5 below:

Formula 5: $UMI = (CLP_{pre\text{-}use} + CLP_{post\text{-}use}) * 0.5$

In the following sections, the results calculated according to the mentioned scope and methods are outlined.

5 Results

The three methods were applied to the one apartment module based on mentioned system boundaries in section 0. In this chapter, all the results will be assessed and compared to get an overview of the relationship between these methods and DfD in this particular case.

5.1 Comparing the results of LCA

Table 5 shows the system boundary of different options calculated by the NS3720 and their analyzed GWP results per square meter of the used floor area (UFA or BRA) of the module. Option 1 was calculated in two variations: The O1 with modules produced in Estonia and O1 with modules produced in Norway. The same variations were evaluated for O2 by adding 5% waste in A5 to each one, creating four different versions. The O3 version considered Norway as a production site and the versions were varied in the amount of material entering the cycles.

What stands out from Table 5 is that variations with Estonia as the modules production site have less emission compared to the ones in Norway. This led to the least emissions for O2Est. by 218.52 kgCO_2/BRA(m^2). Whereas the O3Nrw. emits the most CO_2/m^2 among the calculated options, and even with less mass, the O3 has the highest GWP result. The results illustrate that the variations of O1 have more emissions than O2, due to the extra material mass accounted for in A1-A3 of the first cycle.

The results of GWP(CO_2/BRA(m^2)) for different variations of the three main options calculated by Futurebuilt Zero are presented in Table 6. O2Est's results show the lowest amount of CO2 emissions at 122.10 (kgCO_2/m^2), while O3Nrw emits the most at 218.40 (kgCO_2/m^2).

Table 5 System boundary and Results of NS3720 calculations

NS3720		First Cycle							Second Cycle							Results
	Option code	Module A1-A3	Module A4	Module A5	Module B1	Module B4	Module C2	Module C3	Module A1-A3	Module A4	Module A5	Module B1	Module B4	Module C2	Module C3	(KgCO2/BRAm2)
Option 1 (O1)	O1 Est.	X	Materials to Estonia and then to site	no waste	X	X Transport to site	Site to storage**	0	0*	Storage to site**	0	X	X Transport to site	X	X	260.32
	O1 Nrw.	X	Materials to Norway and then to site	no waste	X	X Transport to site	Site to storage**	0	0*	Storage to site**	0	X	X Transport to site	X	X	267.87
Option 2 (O2)	O2 Est.	Less material used than O1	Materials to Estonia and then to site	no waste	X	X Transport to site	Site to storage**	0	0*	Storage to site**	0	X	X Transport to site	X	X	218.52
	O2 Nrw.	Less material used than O1	Materials to Norway and then to site	no waste	X	X Transport to site	Site to storage**	0	0*	Storage to site**	0	X	X Transport to site	X	X	224.96
	O2 Est. 5%w.	Less material used than O1	Materials to Estonia and then to site	5% waste***	X	X Transport to site	Site to storage**	0	0*	Storage to site**	0	X	X Transport to site	X	X	224.06
	O2 Nrw. 5%w.	Less material used than O1	Materials to Norway and then to site	5% waste***	X	X Transport to site	Site to storage**	0	0*	Storage to site**	0	X	X Transport to site	X	X	229.88
Option 3 (O3)	O3 Nrw.	Same amount of material as O1	Materials directly to site	10-15% waste	X	X Transport to site	X	X	X	Storage to site**	10-15% waste	X	X Transport to site	X	X	326.95
	O3 Nrw. Less mass	Less material used than O1	Materials directly to site	10-15% waste	X	X Transport to site	X	X	X	Storage to site**	10-15% waste	X	X Transport to site	X	X	275.37

* if there is a replacement in this stage, the emission of the replacement was added as A1-A3

** storage is in Norway

***5% of waste is not accounted for Windows and Doors

X= the module is calculaated based on the calcultion method in Reduzer

🟩 Best Option 🟥 Worst Option place

Table 6 System boundary and Results of Futurebuilt Zero calculations

FBZ		First Cycle						Second Cycle								Results (KgCO2/BRAm2)
	Option code	Module A1-A3	Module A4	Module A5	Module B1	Module B4	Module C3	Module D-1st cycle	Module A1-A3	Module A4	Module A5	Module B1	Module B4	Module C3	Module D	
Option 1 (O1)	O1 Est.	X	Materials to Estonia and then to site	no waste	X	X Transport to site	0	X	0*	Storage from and to site**	0	X	X Transport to site	X	X	152.54
	O1 Nrw.	X	Materials to Norway and then to site	no waste	X	X Transport to site	0	X	0*	Storage from and to site**	0	X	X Transport to site	X	X	164.10
Option 2 (O2)	O2 Est.	Less material used than O1	Materials to Estonia and then to site	no waste	X	X Transport to site	0	X	0*	Storage from and to site**	0	X	X Transport to site	X	X	122.10
	O2 Nrw.	Less material used than O1	Materials to Norway and then to site	no waste	X	X Transport to site	0	X	0*	Storage from and to site**	0	X	X Transport to site	X	X	131.65
	O2 Est. 5%w.	Less material used than O1	Materials to Estonia and then to site	5% waste***	X	X Transport to site	0	X	0*	Storage from and to site**	0	X	X Transport to site	X	X	131.19
	O2 Nrw. 5%w.	Less material used than O1	Materials to Norway and then to site	5% waste***	X	X Transport to site	0	X	0*	Storage from and to site**	0	X	X Transport to site	X	X	140.74
Option 3 (O3)	O3 Nrw.	Same amount of material as O1	Materials directly to site	10-15% waste	X	X Transport to site	0	X	X	Storage from and to site**	10-15% waste	X	X Transport to site	X	X	218.40
	O3 Nrw. Less mass	Less material used than O1	Materials directly to site	10-15% waste	X	X Transport to site	0	X	X	Storage from and to site**	10-15% waste	X	X Transport to site	X	X	181.38

* if there is a replacement in this stage, the emission of the replacement was added as A1-A3

** storage is in Norway (C2 1st cycle+A4 2nd cycle)

*** 5% of waste is not accounted for Windows and doors.

X= the module is calculaated based on the calcultion method in Reduzer

🟩 Best Option 🟥 Worst Option place

By comparing the two tables (Table 5 and Table 6) O2Est and O3Nrw have the lowest and highest emissions respectively, in both calculation methods, and O1 stood between O2 and O3. Moreover, the total CO_2 emission of O2Nrw was almost as much as the total CO_2 emissions of O2Est 5%W in both methods. Overall, Futurebuilt Zero calculated 33-44% less Total CO_2 than NS3720, due to the difference between calculating negative emissions and allocations. (Figure 14)

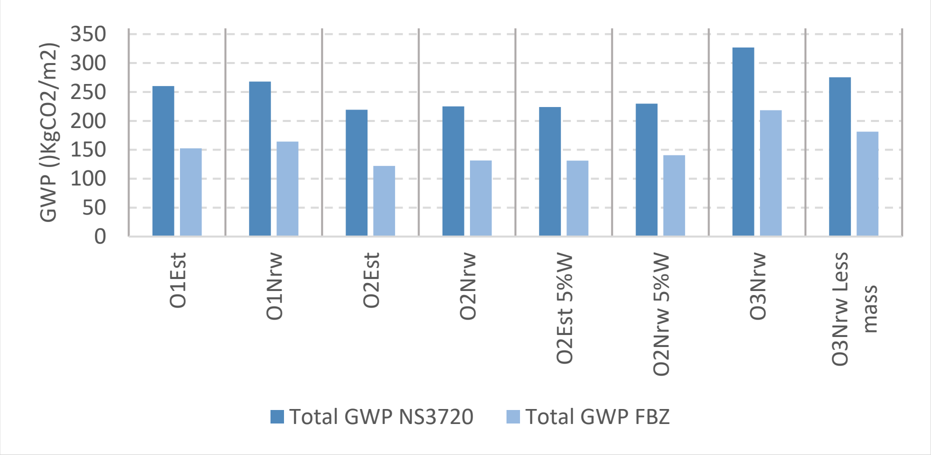


Figure 14 Total GWP results' comparison NS3720 and Futurebuilt Zero

In a more detailed study, the second cycle in O1 and O2 in both calculation methods has less GWP than the first cycle. (Figure 15) This can reflect the effect of A1-A3, which was assigned 0 for products that would remain in the component throughout the next cycle.

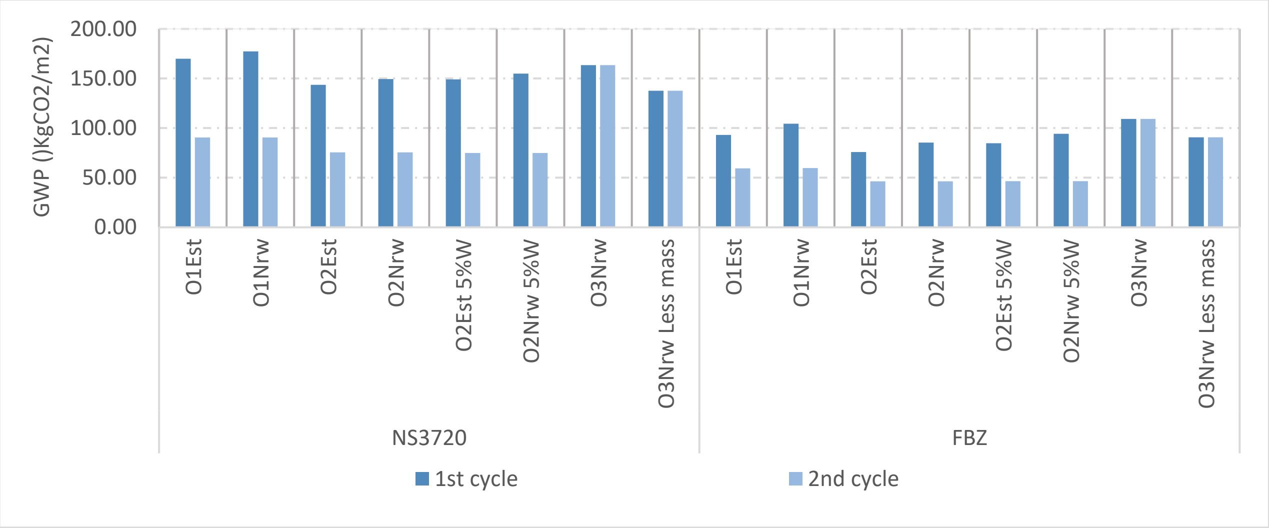


Figure 15 GWP for each cycle- NS3720 and Futurebuilt Zero

The charts below, (Figure 16 and Figure 17)demonstrate the emissions during different life cycle modules for three sample variations. These variations had the most applied changes in their option group. Besides the difference between the system boundary of NS3720 and Futurebuilt Zero in this thesis, during similar modules (A1-A3, A4, A5, B1, B4, and C3), both calculation methods show a similar trend.

Moreover, in the module's total emissions for each option, the A1-A3 are responsible for the most emissions, followed by A4 in Futurebuilt Zero and B4 in NS3720. However, the A1-A3 for the second cycle for O1 and O2 did not dominate the emissions and gave its place to B4 in the second cycle. On the other hand, in Futurebuilt Zero, module D and B1, and NS370 module B1 have positive impacts by absorbing CO2.

Overall, (Figure **16** and Figure **17**) show that the total A1-A3 modules of the first cycle were the most contributors to the last result. Therefore, by paneling, the final module and cutting down the extra materials, which were required for the modular option, all the GWP results influenced by the mass of O2 dropped significantly. This was an advantage that O2 had in the calculations compared to O1.

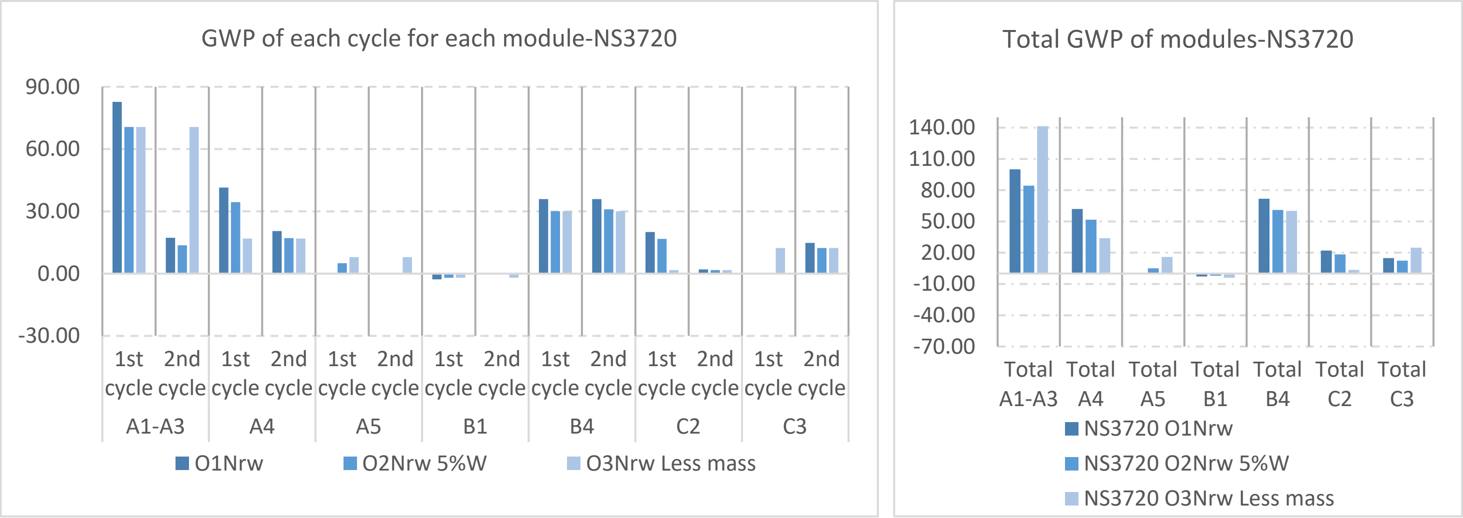


Figure 16 Modules' GWP in three selected options- NS3720

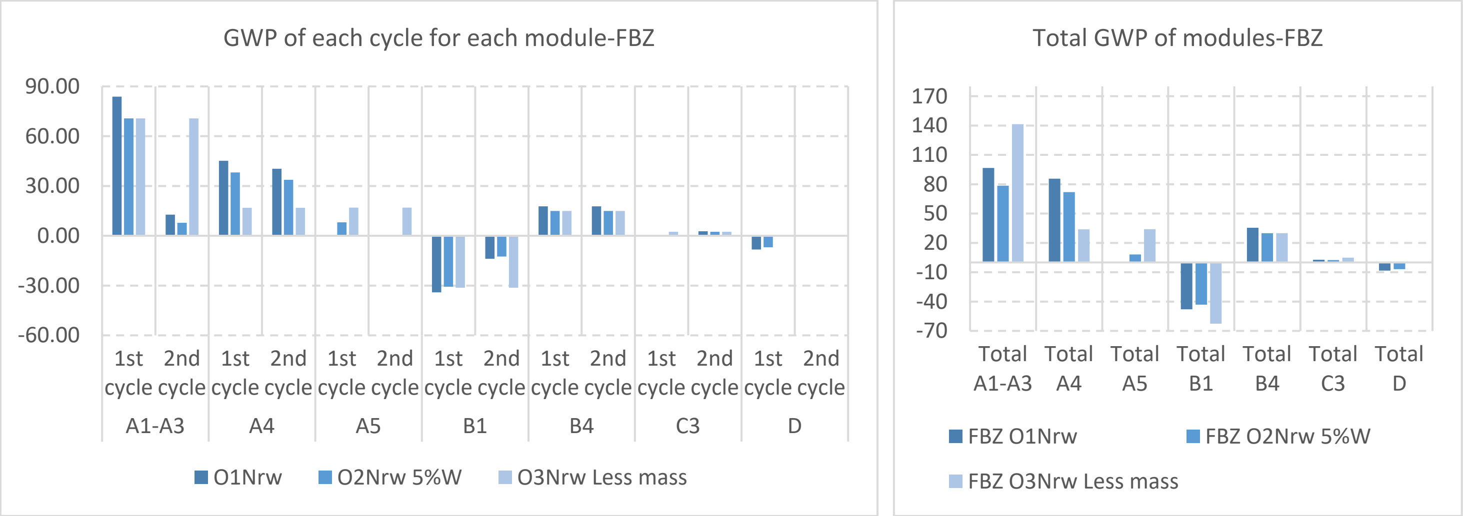


Figure 17 Modules' GWP in three selected options- Futurebuilt Zero

Looking more into the changing transport distance from Estonia to Norway, the bar chart (Figure 18) presents the increase percentage of emissions due to this change. The most significant effect refers to the O2 option in Futurebuilt Zero by a 9.55% increase for changing the production site from Estonia to Norway.

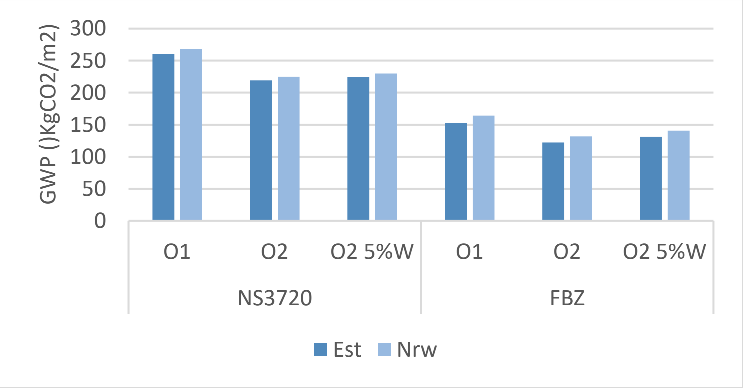


Figure 18 Transport impact on the GWP results in NS3720 and Futurebuilt Zero

Calculations according to Table 1 show that a material like Gypsum board with a density of 9.152kg/m^2, when shipped 1000km has 0.03kgCO$_2$e/kg emissions, whereas when it transferred 1000 km by truck it emits 0.167 kgCO$_2$e/kg. Therefore, transferring the gypsum board to the module production company in Norway and to the site, assumed 1000km by truck, emits 1.53 kgCO$_2$e/m^2, and transferring the same gypsum board to Estonia and to the building site, assumed 4000Km by ship, emits 1.11 kgCO$_2$e/m^2. This transportation by truck emits 38% more emissions than transportation by ship.

Regarding materials' amount, in calculations of O3 in Futurebuilt Zero, reducing the material input resulted in 16.9% less emission, and in NS3720 this amount was 15.7%. Similarly, the calculation for 5% waste in O2, FutureBuilt Zero, and NS3020 accounted for a ≈7% and 2% increase in GWP.

Turning to the building's components' GWP results, almost all the highest and lowest emitting components vary between 2 or 3 components in both calculation methods. (Table 7 and Table 8) For example, Floor dry 28.7cm, the internal wall wet 32.2cm, and the external wall dry 32.1cm showed the two highest emissions compared to other components. The ranking between them changed when half of the internal wall 32.2 cm was accounted for in calculations of O2 and O3. The highest calculated portion of emissions calculated by NS3720 and Futurebuilt Zero was Int. wall wet O1Nrw by 19.3% and 20.0% respectively. The highest portion of emissions varies more in Futurebuilt Zero than NS3720. On the other hand, the two lowest emissions belong to the internal wall dry 13 cm and 10cm, without accounting for the omitted Ceiling wet 26.7cm in the options with less material entry.

Table 7 Fraction of CO2 emissions by elements- NS3720

Components	O1Est	O1Nrw	O2Est	O2Nrw	O2Est 5%W	O2Nrw 5%W	O3Nrw	O3NrwLess mass
Ext. wall wet 32.1cm	4.9%	4.9%	5.8%	5.9%	5.8%	5.9%	5.1%	6.1%
Ext. wall dry 32.1cm	9.8%	8.9%	11.6%	10.5%	11.8%	10.7%	10.2%	12.1%
Door Balcony	2.5%	2.5%	3.0%	3.0%	2.9%	2.9%	2.0%	2.4%
Door unit	2.1%	2.1%	2.5%	2.5%	2.4%	2.4%	2.2%	2.6%
Window Balcony	6.0%	5.9%	7.1%	7.0%	7.0%	6.9%	6.1%	7.3%
Window side wall	1.4%	1.4%	1.6%	1.6%	2.1%	2.1%	1.9%	2.2%
Int. wall dry 13 cm	0.4%	0.4%	0.5%	0.5%	0.5%	0.5%	0.4%	0.5%
Int. wall dry 10 cm	0.6%	0.7%	0.74%	0.79%	0.75%	0.80%	0.7%	0.8%
Int. wall wet 32.2 cm	19.3%	19.0%	11.8%	11.6%	11.4%	11.3%	16.6%	9.9%
Int. wall wet 17 cm	9.3%	9.0%	11.4%	11.0%	11.1%	10.8%	7.5%	8.9%
Int. wall dry 29.2 cm	4.4%	4.7%	2.6%	2.8%	2.7%	2.9%	5.5%	3.3%
Door rooms	6.9%	7.0%	8.2%	8.3%	8.0%	8.2%	7.2%	8.6%
Floor dry 28.7 cm	10.4%	11.3%	12.4%	13.4%	12.6%	13.6%	11.4%	13.5%
Floor wet 28.7 cm	8.6%	8.5%	10.4%	10.3%	10.2%	10.1%	7.4%	8.8%
Ceiling dry 26.9 cm	8.8%	9.0%	10.4%	10.7%	10.6%	10.9%	11.0%	13.1%
Ceiling wet 26.7 cm	4.5%	4.7%	-	-	-	-	4.7%	-
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table 8 Fraction of CO2 emissions by elements- Futurebuilt Zero

Components	O1Est	O1Nrw	O2Est	O2Nrw	O2Est 5%W	O2Nrw 5%W	O3Nrw	O3Nrw Less mass
Ext. wall wet 32.1cm	4.3%	4.3%	5.7%	5.7%	5.4%	5.4%	4.7%	5.6%
Ext. wall dry 32.1cm	11.3%	9.4%	14.1%	11.7%	14.4%	12.1%	11.6%	13.9%
Door Balcony	3.3%	3.3%	1.9%	2.0%	1.8%	1.9%	2.67%	3.21%
Door unit	1.3%	1.3%	1.5%	1.5%	1.5%	1.5%	1.8%	2.1%
Window Balcony	5.2%	5.0%	6.4%	6.1%	6.1%	5.8%	5.8%	6.9%
Window side wall	1.6%	1.5%	1.9%	1.8%	1.8%	1.7%	1.7%	2.1%
Int. wall dry 13 cm	0.5%	0.5%	0.6%	0.6%	0.6%	0.6%	0.6%	0.7%
Int. wall dry 10 cm	0.8%	0.8%	0.98%	1.02%	0.98%	1.02%	0.90%	1.09%
Int. wall wet 32.2 cm	20.0%	19.0%	12.5%	11.8%	12.1%	11.5%	17.4%	10.4%
Int. wall wet 17 cm	9.8%	9.0%	12.2%	11.2%	11.6%	10.8%	7.8%	9.4%
Int. wall dry 29.2 cm	5.1%	5.4%	3.2%	3.4%	3.2%	3.4%	6.4%	3.9%
Door rooms	3.8%	4.0%	3.9%	4.2%	4.4%	4.6%	2.8%	3.3%
Floor dry 28.7 cm	11.4%	12.5%	14.3%	15.5%	15.1%	16.2%	14.0%	16.8%
Floor wet 28.7 cm	9.6%	9.1%	12.0%	11.4%	11.6%	11.1%	8.2%	9.8%
Ceiling dry 26.9 cm	7.1%	9.7%	8.9%	12.0%	9.4%	12.3%	8.8%	10.6%
Ceiling wet 26.7 cm	5.1%	5.2%	-	-	-	-	5.1%	-
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Overall, the best option regarding low emissions is the panelized DfD option with less mass than O1 and production’s site in Estonia. For reducing this amount, it is possible to change the choice of the material for the floor in the dry zone or wall component in the wet and dry zone.

5.2 Comparing the result of CE

Table 9 explains the UMI system boundary and the result of each option. The percentage of UMI results illustrates the potential percentage of that option to be a circular module. Therefore, the O1 DfD shows the highest possibility of circularity by 82.28%, whereas the O3 can be considered the worst option for circularity among all options by UMI=63.47%.

What stands out from this table (Table 9), is that the reducing material only affects 0.28% in O2 and 0.85% in O3. This causes them to have less circularity potential than O1, even with less material.

Table 9 System boundary and Results of UMI calculations

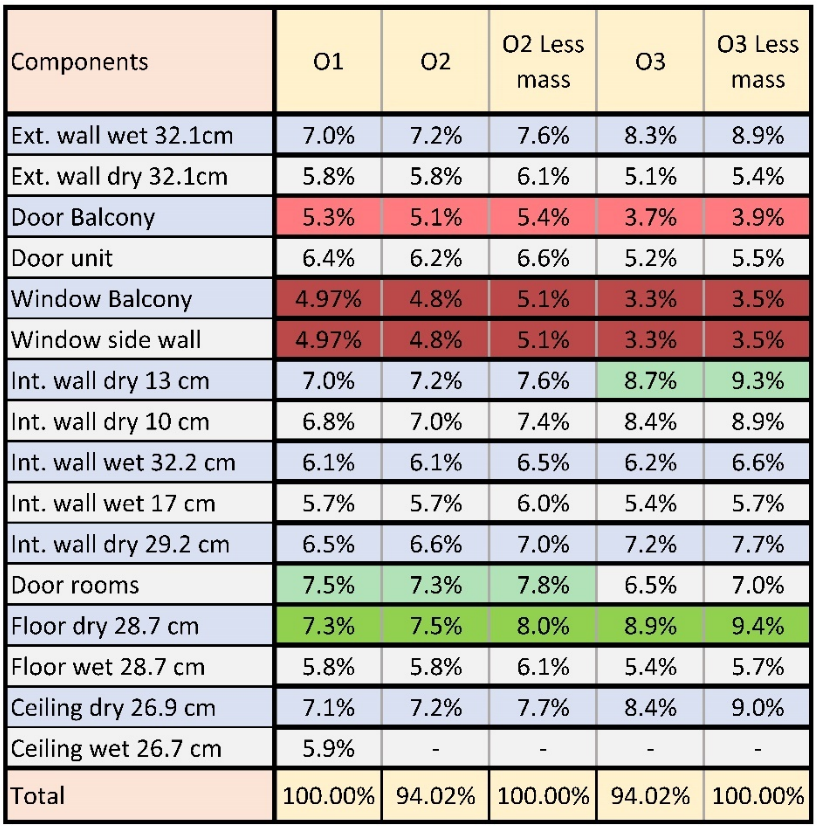
UMI		First and Second Cycle								Results (percentage)
	Option code	Mass kg/m2	Mass composition pre-use	Mass composition post-use	MLP	SD	UD	Fw	Fv	
Option 1 (O1)	O1	X	X	Reuse	100%	Reuse	X	1	1	82.28%
Option 2 (O2)	O2	X	X	Reuse	100%	Reuse	X	0.9	1	79.45%
	O2 Less mass	Less material used than O1	X	Reuse	100%	Reuse	X	0.9	1	79.68%
Option 3 (O3)	O3	X	X	X	X	X	X	X	X	63.17%
	O3 Less mass	Less material used than O1	X	X	X	X	X	X	X	63.35%

X= the module is calculated based on the collected info from relevant sources

🟩 Best Option 🟥 Worst Option

Looking into the UMI of the components, (Table 10) windows have the least portion among other elements, by 3.5%-5.1% in different options. Notably, the windows' size was not involved in the results because the UMI is calculated based on the mass (kg/m2), and not the amount of product used in the module. Moreover, the most contributing element in increasing the UMI was Floor dry 28.7cm in all the options by an average of 8.42%.

Table 10 Fraction of elements' contribution to UMI results



Components	O1	O2	O2 Less mass	O3	O3 Less mass
Ext. wall wet 32.1cm	7.0%	7.2%	7.6%	8.3%	8.9%
Ext. wall dry 32.1cm	5.8%	5.8%	6.1%	5.1%	5.4%
Door Balcony	5.3%	5.1%	5.4%	3.7%	3.9%
Door unit	6.4%	6.2%	6.6%	5.2%	5.5%
Window Balcony	4.97%	4.8%	5.1%	3.3%	3.5%
Window side wall	4.97%	4.8%	5.1%	3.3%	3.5%
Int. wall dry 13 cm	7.0%	7.2%	7.6%	8.7%	9.3%
Int. wall dry 10 cm	6.8%	7.0%	7.4%	8.4%	8.9%
Int. wall wet 32.2 cm	6.1%	6.1%	6.5%	6.2%	6.6%
Int. wall wet 17 cm	5.7%	5.7%	6.0%	5.4%	5.7%
Int. wall dry 29.2 cm	6.5%	6.6%	7.0%	7.2%	7.7%
Door rooms	7.5%	7.3%	7.8%	6.5%	7.0%
Floor dry 28.7 cm	7.3%	7.5%	8.0%	8.9%	9.4%
Floor wet 28.7 cm	5.8%	5.8%	6.1%	5.4%	5.7%
Ceiling dry 26.9 cm	7.1%	7.2%	7.7%	8.4%	9.0%
Ceiling wet 26.7 cm	5.9%	-	-	-	-
Total	100.00%	94.02%	100.00%	94.02%	100.00%

The charts below (Figure 19 and Figure 20) show the $\text{CLP}_{\text{(pre-use and post-use)}}$ percentage of different components calculated in different options. The $\text{CLP}_{\text{pre-use}}$ was based on the combination of the percentage of recycled certified material, new non-certified renewable, and new-certified renewable in a component. Figure 19 depicts that in all options, the $\text{CLP}_{\text{pre-use}}$ stays the same for each component. On the other hand, $\text{CLP}_{\text{post-use}}$ was calculated by combining the percentage of possible end-of-life scenarios, which were reusing, recycling, downcycling certified, and energy recovery certified, and Figure 20 illustrates the difference between the $\text{CLP}_{\text{post-use}}$ of elements. As a result, O1 has the highest $\text{CLP}_{\text{post-use}}$, then O2, and finally O3. Moreover, both the $\text{CLP}_{\text{pre-use}}$ and $\text{CLP}_{\text{post-use}}$ in options 2 and 3 with and without material reduction stay the same, except the ceiling of the wet zone which was omitted.

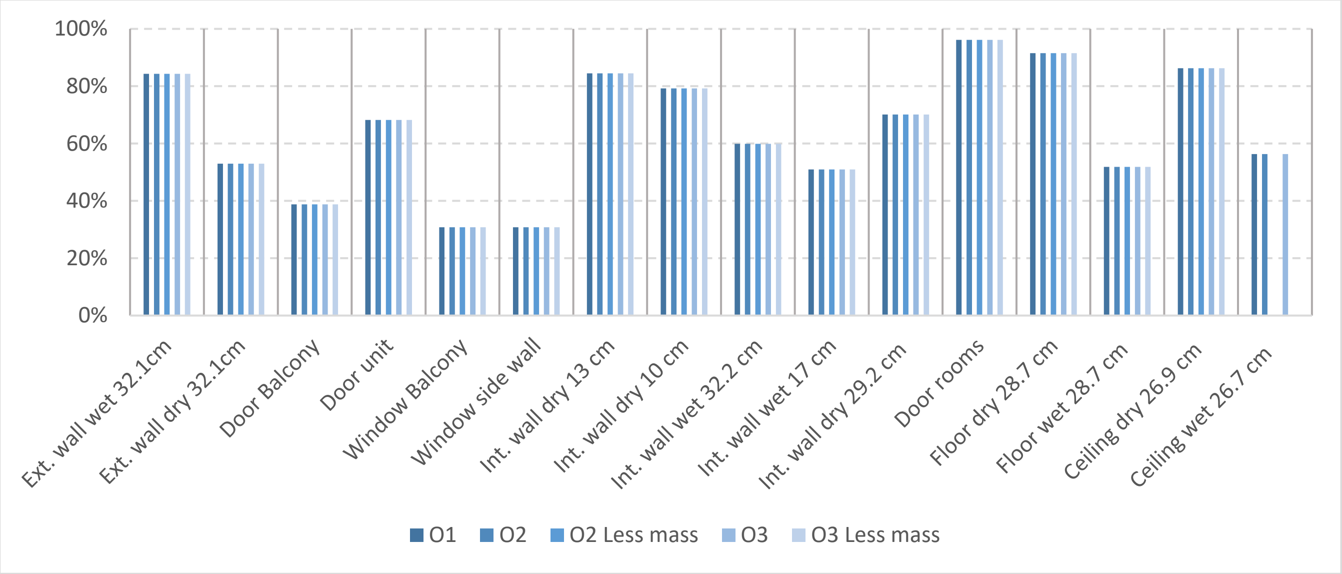


Figure 19 CLP pre-use

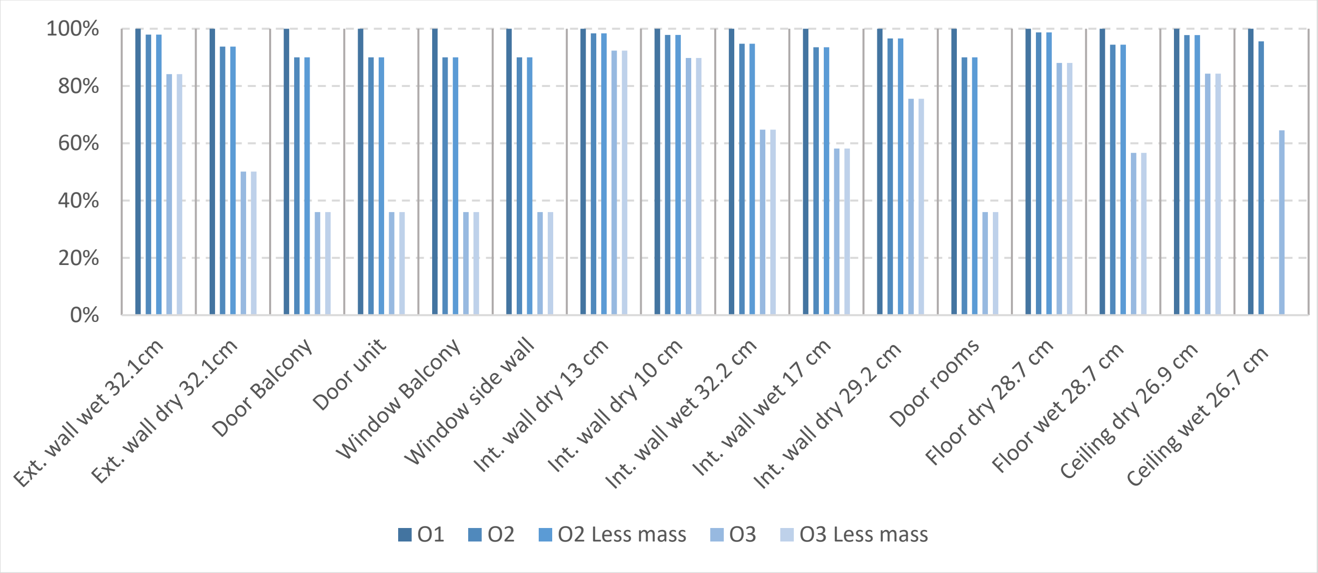


Figure 20 CLP post-use

The bar chart of UMI of components, Figure 21, in most of the components, the results of UMI in O1 and O2 are very close to each other, while O3 has lesser percentages. All in all, besides the ceiling wet 26.7cm, all other components have the result of O2=O2 Less mass, and O3=O3 Less mass. This shows that the material reduction did not affect the UMI results if a specific percentage of a whole component was reduced.

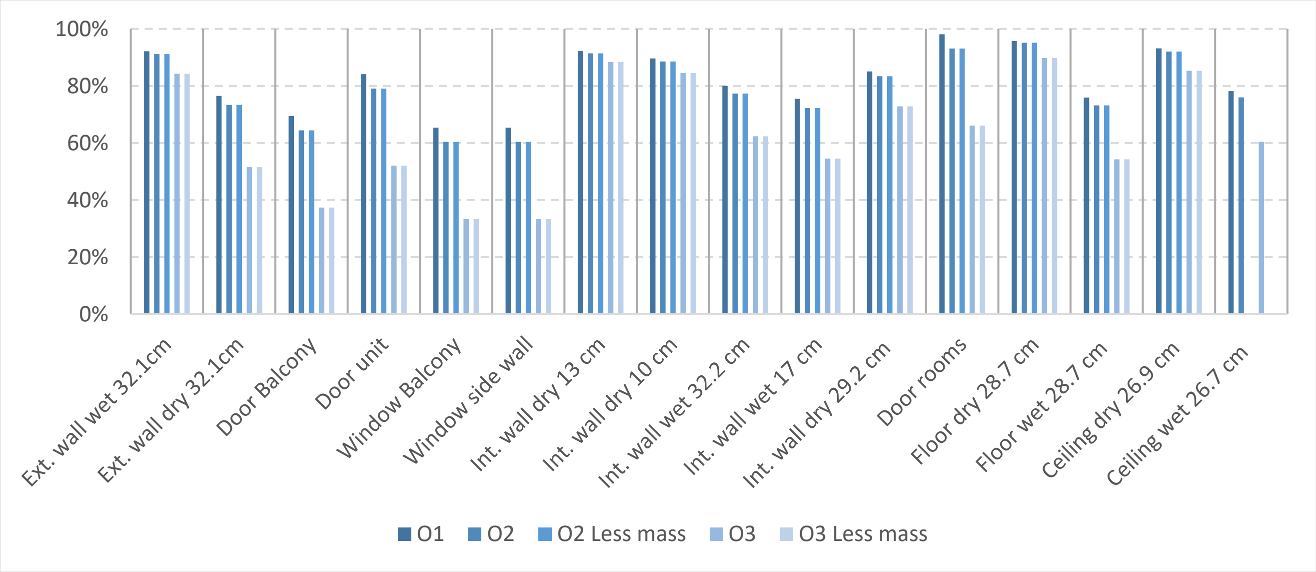


Figure 21 UMI of components

In general, in UMI evaluation, the full module DfD gets the most credit and the on-site construction of the same module gets the least. Moreover, the elements' contribution to the results varied slightly from the lowest 3.9% to the highest 9.4%.

5.3 Comparing LCA and CE

LCA and UMI evaluate different aspects of the product. Therefore, the comparison of details of each evaluation method may not be logical; however, the ranking of options regarding DfD influence on the results can be compared.

Table 11 shows the ranking of options with the best results of each option among its variation. The data suggests that the options with DfD rank better than the option with usual construction on-site. However, this ranking between O2 and O1 varies based on the LCA and CE evaluation. In UMI, option 1 gets the most credit, while in the LCA methods, O2 gets the highest rank.

Table 11 The ranking of options in different evaluation methods

Ranking	NS3720 (KgCO2/BRAm2)	FutureBuilt ZERO (KgCO2/BRAm2)	UMI (Percentage)
1	O2=219.14	O2=122.10	O1=82.28%
2	O1=260.32	O1=152.54	O2=79.68%
3	O3=275.37	O3=181.38	O3=64.02%

By comparing the fractions of elements' contribution in each method, (Table 7, Table 8, and Table 10) what stands out is that the Floor dry 28.7cm, which is among the highest CO_2 emitting components, has the highest circularity potential. Here, the methods' results contradict each other. However, in cases such as Internal wall dry 13 cm, this component emits the least emissions, and it has a high circularity potential.

Moreover, the variation of the results in the elements' LCA methods is wider than the UMI. This means that the different components have more variation in their CO2 emissions than their circularity potential. This variability is presented in Figure 22, Figure 23, and Figure 24.

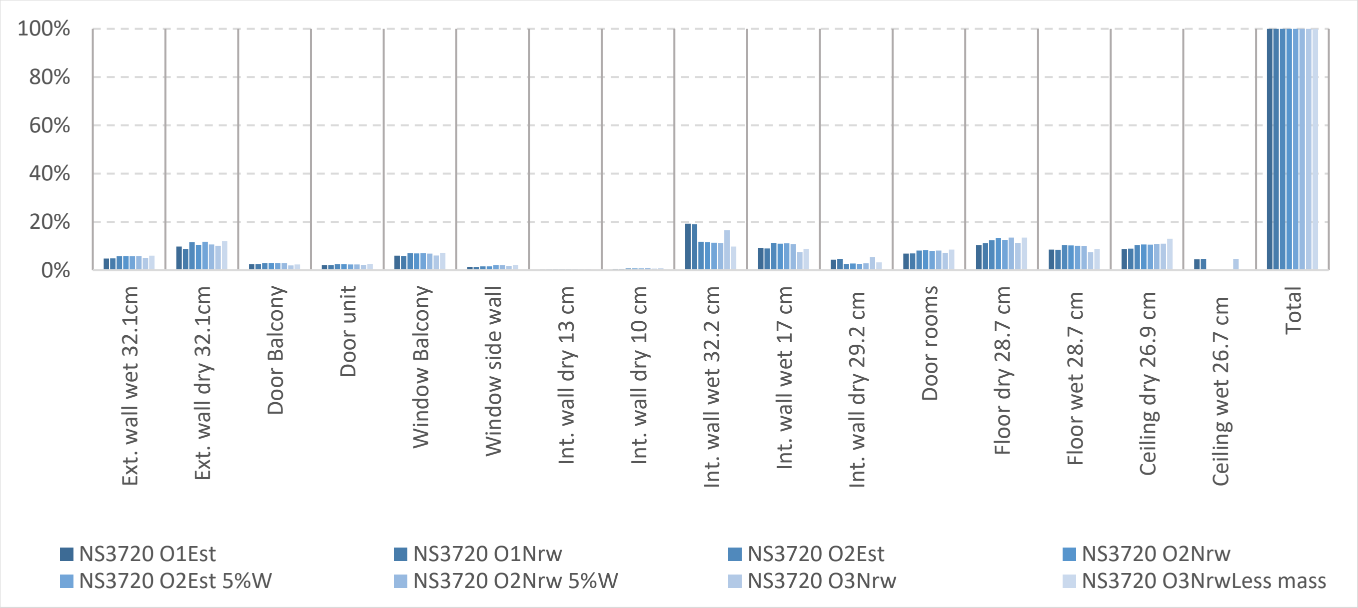


Figure 22 Results' variation bar chart for elements-NS3720

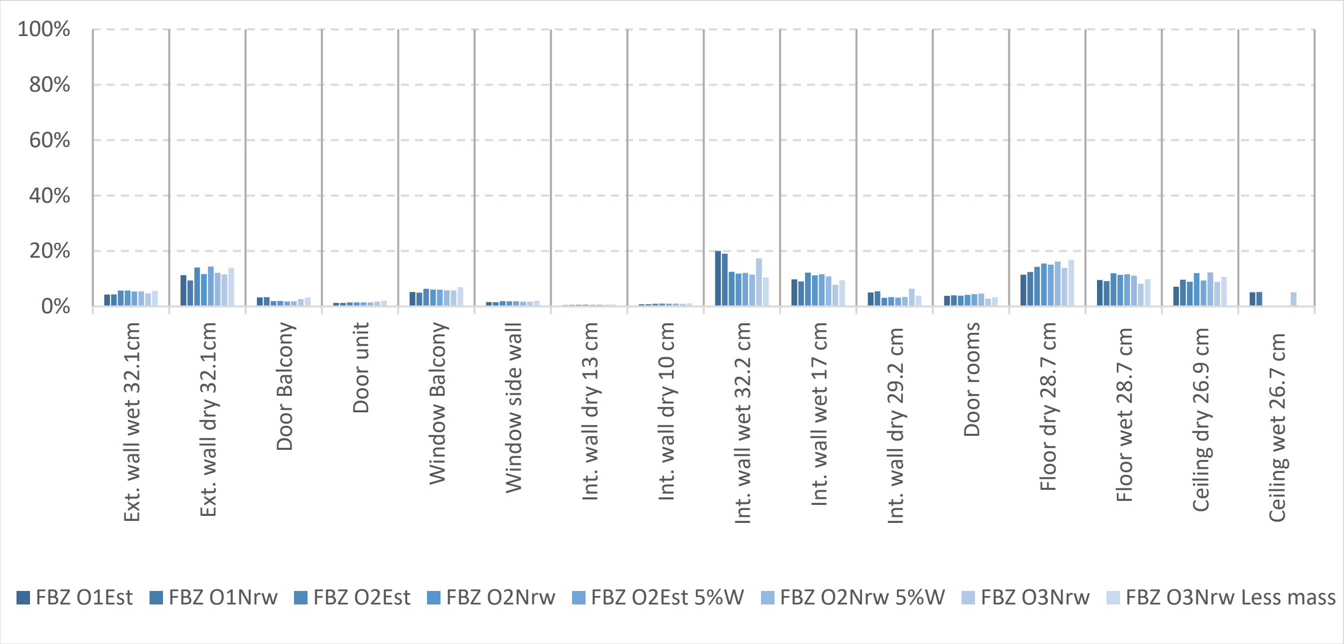


Figure 23 Results' variation bar chart for elements- Futurebuilt Zero

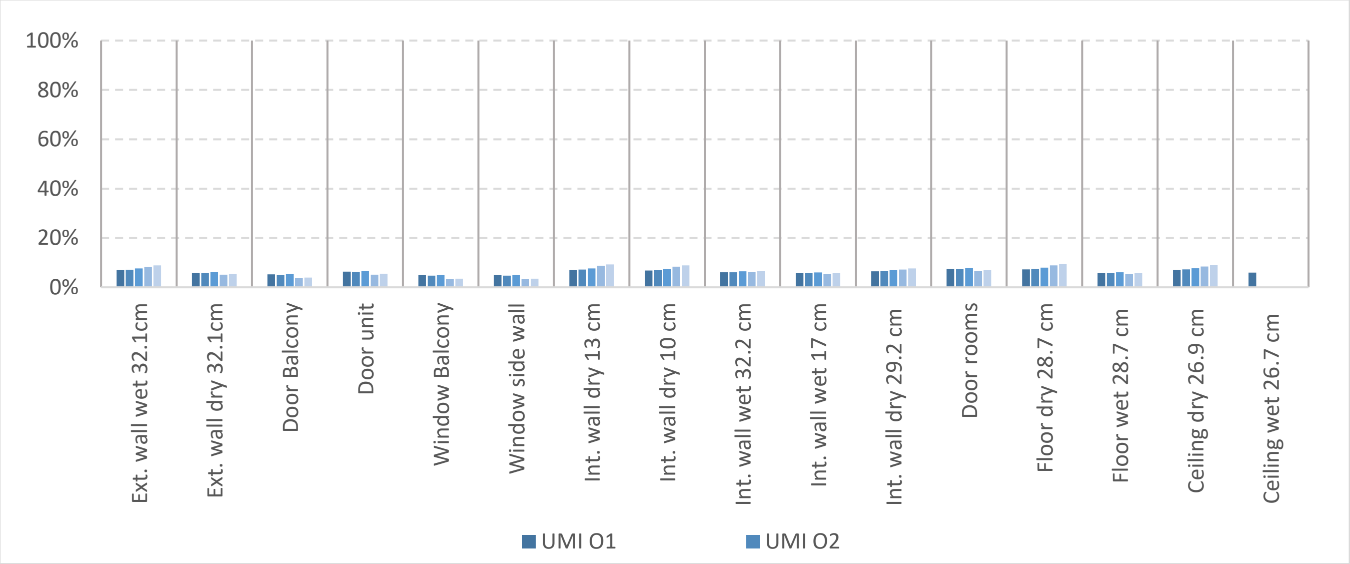


Figure 24 Results' variation bar chart for elements- UMI

To sum up, DfD affects the results in both life cycle assessment methods and the urban mining index for circularity evaluations. The option designed with dismantling in mind gains a positive impact from these calculations. A more detailed relationship between the results and DfD and the reasons behind this impact will be explained in the next chapter.

6 Discussion

In this section, the results of the chosen LCA and CE methods, based on the explained system boundaries described in the methodology section, are discussed. Moreover, the reasons behind the results, some recommendations, and suggestions for future research are presented.

6.1 Interpretation of result of LCA

The results in the chosen LCA methods suggest that designing for dismantling can have a more positive environmental impact than standard construction technology. Moreover, it suggests that in the assigned system boundary, choosing a panelized option can be more beneficial than a modular prefabricated unit. The details about the results are interpreted in the next paragraphs.

In general, the results of Futurebuilt Zero calculations on the options showed lower GHG emissions than the same results calculated by NS3720. The main reason for this is that Futurebuilt Zero accounts for negative emissions of biogenic carbon uptake in the use phase, while NS3720 counts only cement carbonation in B1, and the uptake and emissions of biogenic carbon counteract each other. Another reason is the accounting for reuse and reusability. Futurebuilt Zero considers reuse to reduce A1-A3 emissions by 80% and reusability is credited with 10% of A1-A3 emissions in module D. It recognizes that technological advances and the time factor will reduce the impact of future emissions compared to today's emissions, and it encourages reuse and reusability. Whereas including module D is optional in NS3720 and this method does not have a percentage allocation of A1-A3 for reuse and reusability.

A1-A3: In this study, the material combination of components remains the same in all options. Therefore, those options with less mass would display fewer emissions; no other emissions savings measures were considered. Moreover, O2’s emissions are less than O3Less mass, although they both had mass reductions in the first cycle. This is mostly because of modules A1-A3 in the second cycle. (Figure 16 and Figure 17) The second cycle’s A1-A3 of O3 shows much higher emissions than the same module of O2. In the second cycle of O3, all raw materials were supplied, transported, and manufactured again. Instead, in O2 only the materials which should be replaced after 60 years were provided, and the stored panels of components would directly be transferred to the building site. Thus, the total results of O2 remain higher than O3.

A4: Transport, although it is often not considered highly relevant in LCA, (Jørgensen et al., 1996) has an influence on the results of the case study, as different transport distances change the ranking of results. (Figure 18) As it is shown in Table 1, ships emit less GHG emissions than trucks. Therefore, transporting material, components, or prefabricated modules by ships can be more environmentally friendly than by trucks. For example, based on Table 1, 1 kg of material can be transported by ship 55566 km to emit the same amount of emissions as the transport of 1 kg of material by truck. Although sometimes based on the location of the production company, storage, and site, the options of transport means are limited, and the materials cannot be shipped. Based on Reduzer’s database, many of the materials in this thesis are selected from Norway. Thus, transporting them to the manufacturer in Norway and then to the construction site by truck causes more emissions than transporting them from Estonia to Norway by ship, as it is explained in the results. Therefore, the combination of chosen transport means for each material, resulted in Estonia's options having less emission than Norway's options.

Furthermore, one of the modules in which the O3 has benefits compared to the others is the A4, because of the shorter material's transport distance. (Figure 16 and Figure 17) Module A4 in the first cycle was assigned to calculate the transport of materials to the production company site and then the building site in options 1 and 2. In the next cycle, A4 calculated the distance from the storage in Norway to the building site for these two options. Instead, the transport of materials in the O3 options during the production phase in both cycles was considered directly from the materials' production company to the building site. As a result, there was an extra calculation for transferring the materials from the prefabricating company to the building site in the first two options. Therefore, O3 got less A4 amount in total.

By changing the transport and production choices, the results could have been different. For example, the difference between A4 in O3 and O1-O2 would have been higher if the production company of the modules was located in Norway. The reason for that may lie in the increase of emissions from road transport, as seen in the different results of the Norway and Estonia options.

Another topic to discuss in A4 is the accounting for the transportation of raw materials to the site or the prefabrication company. In the first two options, the transport to the prefabrication company takes place in module A2, while in O3 it occurs in A4. However, in this study, the amount of A2 for transferring the raw material to prefabrication companies in O1 and O2 was allocated to A4 in order to be measurable by Reduzer. Therefore, if this amount had been considered in A2, the benefits for O3 in A4 would have been less than what the current results show.

Transport of goods can be done by ships, trucks, concrete trucks, vans, etc. According to the options, there can be a difference between the number and type of vehicles for each option. The modules, measuring 10m x 9m x 3m in O1, might need bigger containers than separated materials in O3, and the separated materials might require more vehicles for each one of them, while the modules need fewer. Comparing the transport of the panelized option with the modular one, it can be assumed that the panelized one can be transported with fewer vehicles and more various vehicle types than O1. Therefore, this option can be considered if the source and the storage facilities for materials/ components/ modules are finalized in a project. However, since emissions are considered per ton-km rather than the actual volume, the mentioned difference cannot really be taken into account. Here, due to a lack of information, the types of vehicles were only assumed to be ships and trucks, and the number of them was not included in the calculations. For example, 10 tons of crane tilt can transport 10 tons of material with separate packaging in Option 3, while it cannot transport the whole module in Option 1, and it might be able to transport only one/two walls in Option 2 because of the 5-8 length limit. Moreover, the whole module weighs ~18 tons based on Reduzer, and if this truck emits 1.667kgCO2/kg-km, for O3 2 trucks would have been enough without considering the different locations of the manufacturers. For O2, however, 1 truck could have been needed for two components, thus 6 trucks for walls and floors and 1 truck for doors and windows. Therefore, this would have doubled the number of vehicles and the associated GHG emissions.

A5: In this study, only waste was calculated in module A5. The waste, as a result of material loss during the construction phase, was assigned the highest (10-15%) for the O3 option. Besides O3, the only options with waste in A5 are O2Nrw 5%W and O2Est 5%W options which the waste was assigned for 5% of materials on site. Therefore, the A5 amount for O3 shows the highest emissions in both cycles, while this amount for O2 is less than O3 in the first cycle and

0 for the second cycle. (Figure 16 and Figure 17) O1 did not have any waste during construction waste in this study because of the assumption that DfD for modules will not have any waste for construction. However, it can be debatable that the waste for prefabricated options occurs in the A3 in the production company, and companies are reasonably efficient at recycling/reusing their waste in-house. This is much better than collecting waste at the construction site. Therefore, it is not incorrect to consider the waste of the O3 option more than O1 and O2 in general.

In addition to waste, the A5 includes the energy used on the construction site for constructing the building. Therefore, the time for construction and the used equipment should be assigned to get the emission of energy consumption. Among the three options, it might take more time to construct O3 on site, than O2, and at last O1. Moreover, O1 and O2 may require less equipment to be built on-site than O3, which should be proven by documentation of the construction work. Thus, it can be assumed that including construction emissions will increase the emissions in A5. It will increase emissions for all of them, but it might widen the gap (if any) between the less-emission options and the highest in A5. However, these emissions would be shifted to A3 in the prefabricated options because most of the construction would occur in A3. The A3 construction was not considered in this work. To generate a complete picture of the influences of these factors, more data would be needed on tool use and construction/fabrication times for all options. This would also shed light on the question if DfD causes additional impact in the production phase in addition to increased material use.

B1: B1 refers to the use, application, and changes during the operational phase of the materials, and if designed and managed well, carbon and nitrous oxide can be captured and sequestered in new vegetation and soil. (Standard Norge, 2018) Therefore, B1 can have a positive impact. Looking into the negative emissions, B1 calculated the cement carbonation in NS3720 and biogenic carbon uptake and cement carbonation in Futurebuilt Zero. These negative amounts were connected to the material mass containing cement and wood. The B1 negative amount for the second cycle was higher in O3 than in O1 and O2, but it could not compensate for the higher emissions in other modules of O3. Moreover, the most emissions for B1 come from the building's energy use during the use phase. It can be assumed that because of the similarity of building functions in all three options, they will have the same energy usage. However, it might be discussed that the extra material used for O1, will make the building more isolated, so it can use less energy. All in all, the benefits of B1 favor the O3, especially by calculating with the Futurebuilt Zero method.

B2-B3: Modules B2 and B3, which cover maintenance and repairing a part of components, were not calculated by Reduzer. However, based on Kodumaja the modules requires regular maintenance. (SINTEF Building and Infrastructure, 2015) All three options require regular maintenance to reach the highest lifetime for the materials, so it can be assumed that all might emit the same amount of CO2 in the B2 module. In addition, during the lifetime of the building, some elements will require repairing. Repairing a module with DfD can be easier because materials can be easily separated to be repaired, whereas, in the O3 option, there can be some more material loss during the repairing process. However, in DfD options the choosing of layers can play an important role in the amount of emissions in these modules. For instance, if a layer that should be repaired was under a longer-lasting layer, this repair may cause damage to the layer with longer service life and cause extra emissions in these modules. All in all, the total emissions of B2-B3 will favor the DfD options.

B4: This module is about returning a component's full functionality and technically and accounting for all the emissions related to this action. (Norsk Standard, 2019) According to some materials' lifetime such as ceramics, these materials in the components need replacing. The GWP results in B4 show the same emission level for O2 and O3 and more emissions for O1. (Figure 15, Figure 16, and Figure 17) The emissions calculated in the B4 by Reduzer referred to all emissions from the production of that material to the disposal, based on the polluter pays principle. Therefore, O1 emitted more emissions in B4 because it required more material to be reused as a whole module in the next cycle. Based on the same reason, the O2 and O3 had the same level of emissions. In addition, the transport of these replacements was calculated from the raw material production site to the building site. Thus, all transport waste shows the same amount for all three options.

The question here is how much difference in emissions it will make to replace materials in each option. In the options with DfD in mind, the materials are designed to be dismantled easily without so much material loss. Therefore, for replacing a material, the previous materials can be dismantled faster with less energy consumption and the material loss can be minimized. On the other hand, in the O3 option, the dismantling of materials can be more challenging with more material waste, and therefore, more emissions. In the case of calculating energy consumption emissions in B4, the DfD options will get more credit than the usual construction on-site option.

C1: Module C1 covers the demolition or dismantling of a building and on-site sorting of the materials, (Norsk Standard, 2019) and due to the complexity, it is not calculated by Reduzer. In this module, the dismantling effort, machinery, the way of demolition, and energy consumption for these activities can be a reason to promote one option over another one. In the second cycle, it is assumed here that all of the options had the same end of life. They were dismantled, transported to the waste processing unit, and at the end, the materials were disposed of. In this case, when reuse, recycling, and downcycling were not an alternative, the usual demolition was performed without sorting the materials at the end of the second cycle. Thus, all options might have the same energy consumption and effort. Whereas, in the first cycle, the O1 was dismantled like a whole module, so it needed low effort and less machinery, and it can be assumed to take less time for the whole process. Then, O2 compared to O1 would require more effort to dismantle all the components than to be transported to the storage. Finally, the O3 was demolished by the usual demolition method. Based on the work factor in UMI, the usual dismantling for O3 was more than DfD options. Therefore, if this module had been calculated, O3 would have had more emissions than the other two options.

C2: Module C2 covers the transportation of demolished/dismantled products to the waste processing site, including the possible storage. (Standard Norge, 2011) Transporting the dismantled module or panels in O1 and O2 to the storage in the first cycle was assigned in this module. All the same discussion as in A4 about the number of vehicles involved in transportation can also be relevant in this part. Aside from that, the calculated emissions in C2 in the NS3720 method show that O3 has the least emissions than O2 and O1. This is because of the transport distance from the building site to the waste processing center compared to the transportation from the building site to the storage. Therefore, this module favors the O3 option.

C3: Module C3 is the waste processing stage, which in the first cycle of O1 and O2 were calculated as GWP=0. This is because the module and panels were assumed to be transported to the storage unit, and not a waste processing site. In the second cycle, all input materials will reach their end of life, therefore O1 emissions were more than O2 and O3. O3 had the same emissions in C3 in both cycles as O2 had in the second cycle. This result illustrates the benefits of DfD. However, the storage facilities' energy consumption and building emissions, and the emissions regarding maintenance during the storage time can be discussed. It can be studied further how much emissions will be added to the O1 and O2 using a storage facility. Will it be more than the emissions for waste processing and disposal in O3? Or where should the storage facility emissions be allocated?

D: Module D in Futurebuilt Zero, accounted for reuse and reusability potential in options 1 and 3, giving them extra credit in the first cycle. This extra credit belongs to the next cycle but in this thesis, the two cycles were calculated together. Option 3, on the other hand, did not reuse materials for the second cycle, and the reusability potential was not considered in the first cycle. Therefore, Module D had 0 emissions in Figure 17 for O3Nrw Less mass. These small amounts of negative emissions had a positive impact on the results of O1 and O2.

Components: The total floor dry's emissions are among the first two elements with the most emissions and the lowest emissions belong to the internal wall 13cm and then to the internal wall 10cm. This is because of the material composition and each material's emissions. (Figure 17 and Figure 18) Comparing the wet and dry components, no data is suggesting that one has higher emissions than the other. This is because of the difference in the area of these components, and more area of some components made them rank higher in the emissions list. For example, the exterior wall of 32.1cm has two variations, dry and wet, the dry version had more emissions than the wet one, despite the extra layer in the wet wall. The reason is that the area of materials used in the dry one was 3.6 times more than the wet wall, so the extra layer's emissions could not reach that far. Moreover, the emissions on a material level differed in all options, and their variation was calculated by the two methods. This is because of the transport distance, the allocation of biogenic carbon, the reuse/reusability of materials, and the amount of each material in each component.

In general, the two methods' results show a consistency of the LCA methods and prove the credibility of DfD in these assessments. To increase the gap between the benefits of DfD options VS the non-DfD ones, some measures can be taken. For instance, material EoL instead in the second cycle, instead of landfill or energy recovery, can be considered as downcycling and get some benefits in module D of the second cycle. Moreover, the transport vehicles should be chosen by the correct capacity and dimensions to be able to transfer more components at the same time. In this regard, ships are suitable options with enough capacity and lower emissions. Another important factor is reducing the materials which need replacing to reduce the emissions of B4.

6.2 Interpretation of result of CE

The data suggest that the modular option (O1) has the most circularity potential. This promotes the DfD and prefabricated modules for construction, instead of the usual construction on-site (O3). Moreover, O2 was outcompeted by O1, suggesting that the Panelized option has less circularity potential than the modular one.

In Urban mining index calculations, instead of the total weight of materials, only the mass (kg/m^2) of materials was considered, resulting in no positive impact for O2 for utilizing less material. In other words, when the mass of each material in a component reduces by the same percentage, the ratio of calculated items remains the same. Therefore, as can be seen in Figure 19, Figure 20, and Figure 21, the total result for components stays the same percentage, unless the whole component is taken away. This can be a limitation of this method regarding DfD options. For instance, if in DfD options instead of counting for half of the whole shared wall, only some materials were chosen to be included and leaving the rest for the adjacent module, the mass of the materials would have had an influence on the results. In this assumption, the best choice would have been selecting the materials that had higher weight to get higher circularity potential. Therefore, the different mass-cut assumptions can influence the results.

In O1 and O2, the mass (kg/m^2), and other calculation factors were considered the same except for the work factor. The work factor refers to the difficulty of dismantling, and the dismantling of the whole module was considered very low effort (Fw=1), while the dismantling of panels of the module required low effort (Fw=0.9). This factor, even with a 1% difference between O1 and O2, made the results favor O1. For showing the DfD options' benefits, the work factor and the dismantling effort can be one of the logical factors adding to the circularity indicators.

Furthermore, the DfD options consider all the materials to be reused, at the same time, they can be made of recycled and new materials. The value factor refers to the cost/revenue that the waste treatment companies charge for the materials at the end of their life. For DfD options, in which the materials were not sent for the waste treatment, the Fv was assumed to be 1, as no-cost/revenue. This enhanced the UMI of DfD options compared to the O3 because in most cases it cost money to take the materials of components in O3 for waste treatment. This factor was influenced by Norway's market. If the waste treatment companies change their policies and prices in the future, it can affect these results.

Another factor increasing the UMI of DfD options is the Material loop potential. MLP was considered 100% in these options due to the reusing of the whole module or panels. While in O3 this number varied from material to material, and it reached even 0.00% for example in wind barrier. This number was multiplied by work and value factors and then with the mass composition mentioned in the SD category. Then, the mass compositions in post-use were decided by subtracting the item mentioned in the UD category from the total mass. Many of the materials were categorized as disposal and non-certified in the UD category, and this ratio of mass composition was not included in the UMI results. Therefore, the last result in O3 became less than the DfD versions.

Looking more closely at the material composition, however, the total mass reduction did not affect the final results, the mass impact of each material in components can influence the interpretation of the circularity of that material compared to others. It can lead the heavier materials to decide the circularity of a component, as mentioned before. In other words, less UMI can be reached if even a small portion of the heavy material does not have good circularity performance. Moreover, this caused the same UMI results for windows despite their size.

An additional point that can be discussed is the same treatment of UMI with reuse, recycling, downcycling, and energy recovery, whereas reusing and recycling should have more influence. In DfD options, if reusing would have more credits in the UMI, the results would have more gap between the DfD and no DfD options. In this index, which wants to reduce the mining of materials, the circularity index should encourage the reusing and recycling of materials, although weighing these categories can be complex and more research should be done.

The UMIs cover most of the core parameters related to circularity evaluation, e.g., the effort and energy required for disassembly, the material removal costs, the potential end-of-life scenarios, and the loop potential factors. Therefore, it can be suggested that the DfD of modules had the most circularity potential among other options by being assessed with a method that covers different circularity factors. This circularity potential can be increased by choosing raw materials with reused and recycled portions, changing the policy of waste treatment companies that promotes reusing and recycling than disposal, and reducing the work effort by technology advances.

6.3 Interpretation of the relationship between chosen methods

One of the main reasons for this thesis is to show any relations between LCA and CE evaluations and the effect of the differences or similarities regarding the results of DfD. As can be seen from the final results, LCA favors the O2 option over the others, while the UMI recommends O1.(Table 5,Table 6, and Table 9) However, both calculation categories disapprove of selecting the O3 over the DfD. These similarities and differences are due to each method's limitations and strengths, which are explained in the next paragraphs.

All used three methods, NS3720, Futurebuilt Zero, and Urban Mining Index gave credit to reusing the material in two cycles. In calculating two cycles in LCA methods, the A1-A3 for the second cycle did not have any emissions. Moreover, Futurebuilt Zero assigned 10% of A1-A3 to module D because of the reusability of materials in the first cycle. On the other hand, UMI by assigning 100% MLP for reuse materials increase the CLP of post-use and therefore the UMI percentage. This is one of the reasons the DfD options were promoted by all three calculation methods.

In the production phase, the choice of materials affects the GWP amount intensely. For instance, the prefabricated Kodumaja's modules were made of wooden framing and cladding. The wooden materials get credits for biogenic carbon uptake and their emissions are less than the other structural materials such as steel or concrete. If the module components had been made of metal, they could have emitted more GHG emissions. However, on the other hand, because of the high reuse potential of metal in the EoL, the metal framing could have been more circular. Therefore, the different material choices of these modules could lead to different comparison results of the options in LCA. However, this transfer effect is not reflected in the UMI results, i.e., it does not depend on the choice of a manufacturer by location or vehicle type.

Another difference between NS3720, Futurebuilt Zero, and Urban Mining Index is the factors that they consider in the calculations. For instance, LCA methods include the transport and materials' amount effect, whereas the UMI does not involve these factors. As a result, the mass reduction of O2 and O3 did not affect the results, and there was no option for measuring the impact of producing the prefabricated components in Estonia or Norway. On the other hand, it can be very complex to include the assembly and disassembly effort in LCA calculations. The time and energy used in A5 and C1 should be measured in every project to be able to include work effort, like UMI, in the calculations. Therefore, these two LCA methods miss the influence of facilitated disassembly and assembly of components in DfD. Although the DfD options got priority by NS3720 and Futurebuilt Zero, their impact was not included completely.

Regarding the elements and the NS3720, Futurebuilt Zero, and Urban Mining Index evaluations, It stands out from Table 7, Table 8, and Table 10 that the component with almost the most emissions got the highest circularity impact. In other words, floor-dry component can get credits in UMI, while it can be not advantageous in LCA methods. This difference in the impact ratio of these components can cause misjudgment. For instance, if the calculations were only conducted by LCA, choosing the floor dry cannot be advisable, whereas if the calculations were done by the CE method, floor dry can be chosen as the best component. The reason behind this contrast can be two main reasons: 1. not including the total quantity of materials in UMI and 2. Not including the potential of circularity of some materials such as metals in NS3720 and Futurebuilt Zero. Moreover, more embodied energy and carbon may be required in the production cycle to produce high-performance circular materials. Thus, the issue needs to be evaluated from a long-term point of view to make the benefits reasonable in CE, while it will lead to an increase in GWP results in LCA, which is not desirable in most cases. For avoiding this contrast, new allocations and extra factors should be added to these evaluation methods.

By comparing Figure 22, Figure 23, and Figure 24, it is apparent that the contribution of the components in the UMI shows more balance, whereas the result of components calculated by the two LCA methods fluctuates more. The reason is that the module's components had many similar materials with similar characteristics in UMI, and the final result got fewer variations. However, the same materials, by the influence of transport and quantity, reveal more variations in GWP results.

Overall, the final results of these three methods, despite the differences confirm the selection of the O2 and O1 over O3. Thus, the answer to this thesis question about the DfD's relationship with these methods is that these methods can assist in selecting the DfD over on-site constructions.

6.4 Challenges and Limitations

As it is apparent from the results, the LCA and CE can be used for incentivizing DfD over non-DfD options, although there are some shortcomings. Some limitations, their importance, and future solutions are explained in the next paragraphs.

The first challenge that this study had was the collection of data for the modules of the Treet building. After finding the details and plans of these modules from various sources, there was no information about the used material to find the exact EPDs for the materials. However, the final results were based on the comparison of this data, therefore, using the same data for all options minimized the limitation of finding the exact used EPDs.

LCA does not account for multicycles, and different allocations can be used for including the two cycles. This study used the polluter pays principle or cut-off 100:0 allocation method. Limiting the allocation to one option can reduce the certainty of comparison of this result with other research. However, by measuring different allocation methods in future studies, the effect of allocations can be more apparent, and therefore, more comparable.

Another limitation was the number of modules provided by Reduzer. By including some modules such as module C1, demolition, the results could have been closer to reality, and as was discussed before, it could have benefited the DfD options more. Moreover, the reuse and reusability credits were not included in O3, which nowadays even in on-site construction, reusing can be an option. Including this factor can reduce the difference between O3 and DfD options, although the amount of reused material would be less than DfD options in the second cycle, therefore, the general results would remain the same.

The assumptions such as 5% waste on the construction for panelized options, were chosen to be between the waste amount for O3 and O1, and it was based on (Andresen et al., 2021). Although, it could be more realistic if these waste numbers were calculated based on reality and this information was available in the production companies. Another assigned number was the 100 years time horizon for Futurebuilt Zero in Reduzer, rather than 120 years which was chosen as the two cycles' service life in this thesis. A reduction of 1% per year will reduce emissions significantly even after 100 years, and therefore it can be predicted that the TH=120 influence will be small.

In the UMI evaluation, data was collected from various sources, although there were some assumptions for a few materials, such as the Fw of the gypsum board. Moreover, the Fw was based on Dr. Rosen’s thesis in Germany. The correct number of Fw can be calculated in future research and compared to the one in Germany and calculate these three options with the new Fw. The current work factors, however, can be considered almost correct because the main factors are time, resource use, and process type.

6.5 Future work and applications

There had been other studies focused on comparing the LCA-based and circularity evaluation method/indicators. For instance, (De Wolf et al., 2020) suggest that the current approaches to building reuse evaluation do not provide reliable comparisons of results by reviewing and applying the most common methods for LCA of recycled/reused products. However, the results of this thesis were comparable and reliable because it narrowed down the system boundaries and chooses one module with different options instead of different buildings. Since both of these studies were based on restricted scopes and limited system boundaries/allocations, the results of this study and (De Wolf et al., 2020) are contradictory.

It should be mentioned that the results of the LCA and CE indicators were contradictory in most of the articles reviewed by (Adriana Del Borghi, Luca Moreschi, 2020). The reason given was that circularity metrics provide only a partial perspective on a system's environmental performance, and may be masking a shift in burden toward increased energy use or higher levels of emissions. (Adriana Del Borghi, Luca Moreschi, 2020)

In (Rigamonti & Mancini, 2021), it is mentioned that no paper has concluded that circularity indicators by themselves can be used to choose the optimal alternative in circular economy projects. Likewise, evaluations of the system's circularity can complement and improve LCA studies of products/ services that include innovations that can be linked to circular economy schemes; for example, increased recyclability/reusability, reusability/reusability, and length of use phase. The difference in the results of the chosen LCA and CE indicators in this thesis, it can be concluded that conducting both LCA and CE evaluations on a project can lead to a more correct perspective on the environmental performance of that project. However, this cannot be applicable in many projects due to a lack of enough time and budget to do both assessments.

These evaluation methods provide measures that can show the benefits of DfD in the construction industry. Therefore, within the explained system boundaries, this thesis can be used for selecting the prefabricated components with DfD for new buildings rather than the usual on-site construction. However, depending on the method chosen, the selection of prefabricated modules over panels or the opposite may produce different results.

Besides some future research mentioned before, there are some other possibilities that this thesis can be developed and tested. First and foremost, this study can be continued by applying different LCA and CE methods. Secondly, the LCA calculations can be tested with another software, such as One-Click LCA, and the results can be compared with the ones from Reduzer. Third, more detailed information about the construction and demolition can be gathered to add the A5 and C1 to the calculations and get new results. Fourth, these calculations can be done in a module with fewer wooden elements and more cement-base/ steel materials to observe the difference. Finally, the cycles can be calculated with different allocations and assumptions. All these future studies can test the impact of the LCA and CE calculations when DfD is considered from the beginning.

7 Conclusion

Evaluation methods to assess the environmental impact and circularity of a project are designed to identify weaknesses and strengths, then try to reduce the shortcomings, and finally point out opportunities such as introducing DfD into the project. By comparing the results of LCA-based and circularity calculation methods, a broader perspective of a project's impact on society can be covered to draw more accurate conclusions.

DfD can influence the environmental performance of projects by reducing emissions and focusing on recycling and reusability. On the other hand, by quantifying the impact of DfD on the environment, LCA and circularity assessment methods can provide some incentives to prove the value of DfD. Therefore, the selection or nonelection of DfD can be influenced by the analysis of these indicators and their relationships.

This thesis concludes that LCA methods and circularity indicators can have common results in some cases, such as incentivizing DfD over non-DfD projects. Although all methods show the benefits of DfD, Futurebuilt Zero and UMI provide more incentives for DfD in their calculations than NS3720. On the other hand, the comparison of the methods cannot identify the advantages of prefabricated modules or panels over the other. This is due to the contrast of results in this case study's system boundaries.

In general, more studies should be designed to measure the liability of the comparative results of these methods. These future studies should test DfD projects with different inventories, and system boundaries, and expand the varieties of LCA and circularity assessment methods to cover a broader perspective on the relationship between these methods and DfD.

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Appendix 1

This appendix covers similar definitions of the environmental emissions calculation methods.

EPD: The ISO type III Environmental Declaration or the Environmental Product Declaration (EPD) is a concise document, verified and registered by a third party, that provides transparent and comparable information on the environmental performance of a product over its lifecycle. (ISO, 2006) EPD is calculated based on sources in Figure 25. (LCA.no AS, 2023)

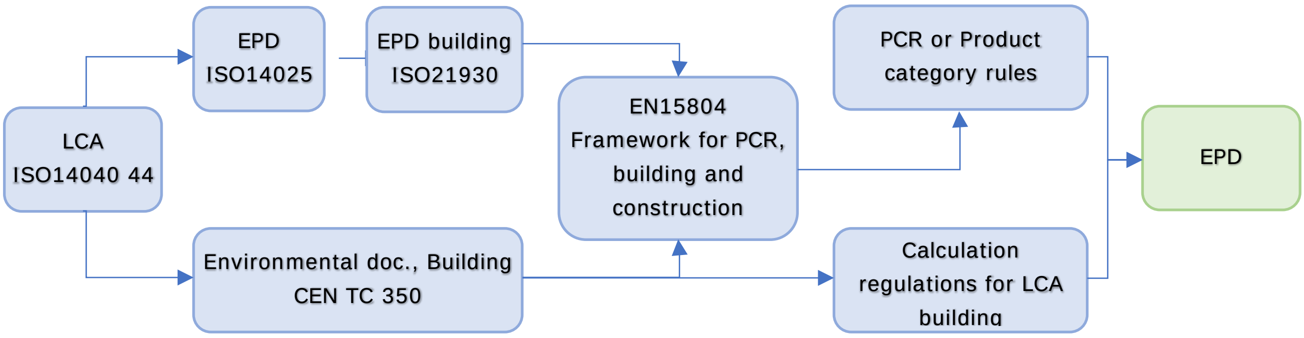

Figure 25 The basis sources of EPDs, adapted from LCA.no

EPDs have different types covering different life cycle modules, but they always have to include modules A1-A3, C1-C4, and D. (Norsk Standard, 2019) Under the following conditions, an EPD may miss out on the mandatory life cycle stages 1. The product or material is physically integrated with other products when installed so that it cannot be physically separated when it reaches the end of its life; 2. A physical or chemical transformation process makes the product or material unidentifiable at end-of-life, and 3. the product/material contains no biogenic carbon, meaning that the declaration of modules C1-C4 and module D cannot be omitted for any product containing biogenic carbon. (Norsk Standard, 2019) EPDs should include data about the estimated service life (Es SL) and additional technical data about the products.

System boundary: The system boundary is all the processes from the early stages of making the product to the end-of-life (EoL), including the remaining service of the product until the end-of-life stage. (Standard Norge, 2011) If the product was made and used, the system boundary will be after the specific stage to the EoL. Therefore, it can be assumed that in reused materials the system boundary will be counted after their production stage. The system boundary should include all stages from the extraction of raw materials, through the manufacturing, distribution, storing, use, and waste treatment, according to the intended use of the study. (EC-JRC, 2012)

Reference service life (RSL): A declared reference service life (RSL) for a building product should be based on its specified technical characteristics and any maintenance or repair required to provide the specified performance during the RSL. (Norsk Standard, 2019)The scenarios should therefore be based on this RSL.

Functional and declared units: Functional Unit refers to a product system's quantified performance used as a reference unit, (Standard Norge, 2006) and Declared unit relates to the quantity of a construction product to be used as the reference unit in an EPD for an environmental declaration based on one or more information modules. (Norsk Standard, 2019) 352 These units indicate to produce data in which the material flows (inputs and outputs) for each module of building material are normalized, in terms of mathematics and common language, a combination of the material flows assigned to the building materials, and an addition of the environmental impacts for the selected lifecycle stages at the building scale. (Norsk Standard, 2019) If a functional unit cannot be defined because of different functionality potentials in the building, or there are no definite scenarios specified for it, the declared unit will be used instead. (Norsk Standard, 2019)

Production stage in LCA: The product stage (or cradle to gate/ A1-A3) includes the supplying of all materials (raw, secondary, reused, or recycled), products/ co-products, and energy, as well as the processing of waste to the end-of-waste state or the disposal of final waste during this stage. (Norsk Standard, 2019) in other words, all procedures in the Technosphere required to provide the functional or declared unit of the product should be included in the system under study. (Norsk Standard, 2019) Moreover, in the Product environmental footprint studies this stage is called “Raw material acquisition and pre-processing”, including resource mining and preprocessing, the transformation of recycled materials, biogenic materials photosynthesis, the cultivation and harvesting of trees or crops, transport within and between mining and preprocessing a manufacturing plants, chemical processing, production, transportation of semi-finished products from one manufacturing process to the next; material component assembly; packaging; waste treatment; employee transportation (if applicable), business trips (if applicable). (EC-JRC, 2012) Therefore, the production stage starts with the extraction of materials and ends with the EoL processes before entering the construction.

Construction process stage: In the construction process stage (A4-A5) contains the transportation of materials, masses, and equipment to and from the construction site, portable and stationary construction equipment, including fuel, the consumption of energy for storage, heating, cooling, curing, dehumidification, lighting, etc., at the building site, and the end production, transportation, and waste management of cuttings, packaging, and other waste materials. (Norsk Standard, 2019) The first transportation part (A4) and the storage part (A5) were assigned as the Product distribution and storage stage in PEF, which include the same energy consumption in the storage facilities and fuel for transporting vehicles. (EC-JRC, 2012)

Use stage: Use phase (B1-B7/8) in LCA methods covers the period after construction work until the demolition. (Standard Norge, 2011) These modules include the use of construction products, equipment, and services and their use for the protection, conservation, mitigation, or control of a building, maintenance, repair, replacement, and refurbishment, energy and water supply, and waste management of final residues in the use stage. (Standard Norge, 2011) This phase can have scenarios that are based on existing regulations, client's demands (e.g., maintenance every 5 years), approved code of practice, usage pattern, manufacturer's information, and service life. (Standard Norge, 2011) Moreover, the use phase in PEF refers to all the activities from when the consumer owns and starts using the product until it demolition for waste processing. (EC-JRC, 2012) For example, consumption patterns, location, time, transportation, resource consumption during use, product repair, and maintenance during this stage. (EC-JRC, 2012) In addition, circular economy refers to the use phase as a stage starting from reaching a product to the first users until when it is no longer reused. (Ellen Macarthur Foundation and Granta Design and Life, 2019)

End of life stage: This stage starts with the product cannot be used again or it is discarded by the users and it ends with all the products being removed from the site and they are returned to nature as waste or entering another cycle. (EC-JRC, 2012)(Standard Norge, 2011) This stage includes the disassembly, collection, and transportation of products and packaging at the EoL, shredding and sorting, waste treatment, incineration, and disposal. (EC-JRC, 2012)

Module D/ Benefits and loads beyond system boundary: This module reflects the potential net impacts of reuse, recovery, recycling, and energy carriers leaving as a secondary material pr fuels. (Norsk Standard, 2019) The energy recovery from incineration or landfilling should be accounted for in module D, and the required processes for using secondary materials ad primary ones also will be included in this module. (Norsk Standard, 2019) Moreover, the excess energy from the B6 module should be allocated to module D, (Norsk Standard, 2019) although this energy production/consumption of the building was not included in this master thesis.

Appendix 2

This appendix provides details of the walls used in the calculations, including the materials and their area, thickness, volume, and mass.

lemer	Description	Amount	Unit		Material name	Area of material in 1m2 of component	Total area in whole component	Thickness m	Volume m3	Kg/m2
232	exterior wall wet 32.1 c	13.73	m2	1	Gypsum board	1	13.73	0.013	0.17849	9.152
		13.73	m2	2	OSB	1	13.73	0.009	0.12357	5.463
		13.73	m2	3	Mineral wool	0.87	11.9451	0.22	2.627922	17.6
		13.73	m2	4	Wood cladding	1	13.73	0.019	0.26087	10.44898
		13.73	m2	5	Vapor barrier	1	13.73	0.00015	0.0020595	0.185
		13.73	m2	6	Wind barrier	1	13.73	0.00049	0.0067277	0.145
		13.73	m2	7	Mineral wool	1	13.73	0.03	0.4119	2.4
		13.73	m2	8	Wooden frame	0.13	1.7849	0.22	0.392678	105.6
		13.73	m2	9	Membrane	1	13.73	0.0015	0.020595	1.78
					Total					152.774
232	exterior wall dry 32.1 cm	49.67	m2	1	Gypsum board	1	49.67	0.013	0.64571	9.152
		49.67	m2	2	OSB	1	49.67	0.009	0.44703	5.463
		49.67	m2	3	Mineral wool	0.87	43.2129	0.22	9.506838	17.6
		49.67	m2	4	Wood cladding	1	49.67	0.019	0.94373	10.44898
		49.67	m2	5	Vapor barrier	1	49.67	0.00015	0.0074505	0.185
		49.67	m2	6	Wind barrier	1	49.67	0.00049	0.0243383	0.145
		49.67	m2	7	Mineral wool	1	49.67	0.03	1.4901	2.4
		49.67	m2	8	Wooden frame	0.13	6.4571	0.22	1.420562	1.78
										47.17398
234	Door Balcony	2.6814	m2	1	Wooden door wit	1	2.6814			36.03
234	Door unit	2.6814	m2	1	Wooden door	1	2.6814			22.76
234	Window Balcony	7.28	m2	1	Wooden frame wi	1.09	7.9352			34.32
235	Window side wall	3.64	m2	1	Wooden frame wi	0.66	2.4024			34.32
242	interior wall dry 13 cm	12.2	m2	1	Gypsum board	1	12.2	0.026	0.3172	9.152
		13.2	m3	2	Wooden frame	0.07	0.924	0.1	0.0924	48
										57.152

242	interior wall dry 10 cm	20.65	m2	1	Gypsum board	1	20.65	0.026	0.5369	9.152
		20.65	m2	2	Wooden frame	0.07	1.4455	0.07	0.101185	33.6
										42.752
242	interior wall wet 32.2 cm	20.43	m2	1	Gypsum board	1	20.43	0.052	1.06236	36.608
		20.43	m2	2	Membrane	1	20.43	0.0015	0.030645	1.78
		20.43	m2	3	Ceramic tiles	1	20.43	0.018	0.36774	18.65
		20.43	m2	4	Mineral wool	0.93	18.9999	0.19	3.609981	15.2
		20.43	m2	5	OSB	1	20.43	0.018	0.36774	10.926
		20.43	m2	6	Wooden frame	0.07	1.4301	0.19	0.271719	91.2
		20.43	m2	7	Ceramic mortar gl	1	20.43	0.02	0.4086	39.28
										213.644
242	interior wall wet 17 cm	11.4	m2	1	Gypsum board	1	11.4	0.039	0.4446	27.456
		11.4	m2	2	Membrane	1	11.4	0.0015	0.0171	1.78
		11.4	m2	3	Ceramic tiles	1	11.4	0.018	0.2052	18.65
		11.4	m2	4	Wooden frame	0.07	0.798	0.1	0.0798	48
		11.4	m2	5	Ceramic mortar gl	1	11.4	0.02	0.228	39.28
										135.166
242	interior wall dry 29.2 cm	20.43	m2	1	Gypsum board	1	20.43	0.052	1.06236	36.608
		20.43	m2	2	Mineral wool	0.93	18.9999	0.19	3.609981	15.2
		20.43	m2	3	OSB	1	20.43	0.018	0.36774	10.926
		20.43	m2	4	Wooden frame	0.07	1.4301	0.19	0.271719	91.2
										153.934
234	Door rooms	13.407	m2	1	Wooden door	1	13.407			22.64
254	floor dry 28.7 cm	67.8	m2	1	Wooden parquet	1	67.8	0.013	0.8814	7.3359
		67.8	m2	2	Wood particle boa	1	67.8	0.022	1.4916	9.152
		67.8	m2	3	Mineral wool	0.78	52.884	0.245	12.95658	19.6
		67.8	m2	4	Wooden frame	0.22	14.916	0.245	3.65442	117.6
		67.8	m2	5	Steel wire mesh	0.23	15.594	0.245	3.82053	0.9313

										154.6192
254	floor wet 28.7 cm	7.15	m2	1	Ceramic tiles	1	7.15	0.018	0.1287	18.65
		7.15	m2	2	Ceramic mortar gl	1	7.15	0.002	0.0143	39.28
		7.15	m2	3	Concrete	1	7.15	0.033	0.23595	79.2
		7.15	m2	4	Steel mesh	0.05	0.3575	0.002	0.000715	2.3
		7.15	m2	5	Mineral wool	0.76	5.434	0.22	1.19548	17.6
		7.15	m2	6	Wood particle boa	1	7.15	0.013	0.09295	9.75
		7.15	m2	7	Wind barrier	1	7.15	0.00049	0.0035035	0.145
		7.15	m2	8	Membrane	1	7.15	0.0015	0.010725	1.78
		7.15	m2	9	Steel plate 1mm	1	7.15	0.001	0.00715	7.9
		7.15	m2	10	Wooden frame	0.24	1.716	0.22	0.37752	105.6
										282.205
254	roof dry 26.9 cm	67.8	m2	1	Wood particle boa	1	67.8	0.012	0.8136	9
		67.8	m2	2	Mineral wool	0.87	58.986	0.12	7.07832	9.6
		67.8	m2	3	Gypsum board	1	67.8	0.013	0.8814	9.152
		67.8	m2	4	Wooden frame	0.13	8.814	0.12	1.05768	57.6
										85.352
254	roof wet 26.7 cm	7.15	m2	1	Concrete	1	7.15	0.033	0.23595	79.2
		7.15	m2	2	Steel mesh	0.05	0.3575	0.002	0.000715	2.3
		7.15	m2	3	Mineral wool	0.76	5.434	0.22	1.19548	17.6
		7.15	m2	4	Wood particle boa	1	7.15	0.013	0.09295	9.75
		7.15	m2	5	Wind barrier	1	7.15	0.00049	0.0035035	0.145
		7.15	m2	6	Membrane	1	7.15	0.0015	0.010725	1.78
		7.15	m2	7	Steel plate 1mm	1	7.15	0.001	0.00715	7.9
		7.15	m2	8	Wooden frame	0.24	1.716	0.22	0.37752	105.6
										224.275

Appendix 3

Appendix 3 refers to the digitally attached Excel files for all NS3720, FutureBuilt Zero, and UMI calculations for the three options including their variations. The files are uploaded to Inspera as a zip file.

Appendix 4

Appendix 4 provides information about calculating the reused/new and certified and noncertified amounts of windows and doors for use in the UMI calculations.

Interior door materials	Weight of material used in component (Kg)	Percentage of material in the component	Recycle material percentage
HDF plate (wood)	12.95	21.34	0
Particle/chipboard	27.2	44.82	0
Spruce frames	8.19	13.49	0
Glue	0.77	1.27	0
Edging strip	6.05	0.09	0
Frame	9.46	15.59	0
Lockbox & hinges	1.18	1.95	48.0%
Paint and glass	0.66	1.09	0
Firewall	0.22	0.36	0
Total	60.67	100	0.94%

Balcony door materials	Weight of material used in component (Kg)	Percentage of material in the component	Recycle material percentage
Pine timber	25.38	26.29	0
Heat treated timber	0.44	0.46	0
3-layer glass (glass)	56.92	58.95	18%
3-layer glass (spacer)	0.91	0.99	0
3-layer glass (butyl[rubber])	0.06	0.06	0
3-layer glass (sealant)	1.35	1.40	0
Paint	0.72	0.75	0
Aluminum	2.32	2.40	25%
Plastic	0.17	0.18	0
Gasket (seal)	0.66	0.68	0
Metal steal allays	4.07	4.22	0
Sealant to glue	0.17	0.18	0
Additional for aluminum cladding (Aluminum)	3.29	3.41	25%
Additional for aluminum cladding (Plastic)	0.03	0.03	0
Additional for aluminum cladding (Metals)	0.06	0.06	0
Total	96.55	100	12.06%

Apartment door materials	Weight of material used in component (Kg)	Percentage of material in the component	Recycle material percentage
Adhesive & Sealant	0.35	0.58	0
Aluminum	1.21	1.98	25%
Coating materials	1.39	2.29	0
Gasket	0.32	0.52	0
Insulation	1.68	2.76	0
Medium-density fiberboard	16.55	27.11	0
Metal	14.56	23.85	0
Plastic	0.10	0.16	0
Wood	24.88	40.75	0
Total	61.04	100	0.35%

Exterior windows materials	Weight of material used in component (Kg)	Percentage of material in the component	Recycle material percentage
Pine timber	10.48	16.77	0
3-layer glass (glass)	47.96	76.78	18%
3-layer glass (spacer)	0.79	1.27	0
3-layer glass (butyl)	0.03	0.04	0
3-layer glass (sealant)	1.17	1.87	0
Paint	0.29	0.47	0
Aluminum	1.24	1.99	25
Plastic	0.09	0.14	0
Gasket	0.37	0.59	0
Metal steal allays	0.00	0.00	0
Sealant to glue	0.05	0.08	0
Total	62.46	100	14%

Appendix 5

These tables show the MLP assumptions required for the calculation, which are based on the “Manual of Recycling : buildings as Sources of Materials” (Hillebrandt et al., 2019).

Material Name (Option 1)	MLP	SD	UD	FW	FV
Ceramic mortar glue	100.00%	ru	d/nr	1	1
Ceramic tiles	100.00%	ru	d/nr	1	1
Concrete	100.00%	ru	d/nr	1	1
Gypsum board	100.00%	ru	d/nr	1	1
Membrane	100.00%	ru	d/nr	1	1
Mineral wool	100.00%	ru	d/nr	1	1
OSB	100.00%	ru	encr	1	1
Steel mesh	100.00%	ru	rc	1	1
Steel plate 1mm	100.00%	ru	rc	1	1
Steel wire mesh	100.00%	ru	rc	1	1
Vapor barrier	100.00%	ru	d/nr	1	1
Wind barrier	100.00%	ru	d/nr	1	1
Wood cladding	100.00%	ru	encr	1	1
Wood particle board	100.00%	ru	encr	1	1
Wooden frame	100.00%	ru	encr	1	1
Wooden parquet	100.00%	ru	encr	1	1
Wooden door with glass	100.00%	ru	d/nc	1	1
Wooden door	100.00%	ru	d/nc	1	1
Wooden door unit	100.00%	ru	d/nc	1	1
Wooden frame window 1.2*1.65m	100.00%	ru	d/nc	1	1
Wooden frame window 1.0*1.2m	100.00%	ru	d/nc	1	1

RU =Reusing
RC =(Recycling)
DCCR = Downcycling certified
ENCR = Energy Recovery certified
D/N=Disposal and non-certified

Material Name (Option 2)	MLP	SD	UD	FW	FV
Ceramic mortar glue	100.00%	ru	d/nr	0.9	1
Ceramic tiles	100.00%	ru	d/nr	0.9	1

Concrete	100.00%	ru	d/nr	0.9	1
Gypsum board	100.00%	ru	d/nr	0.9	1
Membrane	100.00%	ru	d/nr	0.9	1
Mineral wool	100.00%	ru	d/nr	0.9	1
OSB	100.00%	ru	encr	0.9	1
Steel mesh	100.00%	ru	rc	0.9	1
Steel plate 1mm	100.00%	ru	rc	0.9	1
Steel wire mesh	100.00%	ru	rc	0.9	1
Vapor barrier	100.00%	ru	d/nr	0.9	1
Wind barrier	100.00%	ru	d/nr	0.9	1
Wood cladding	100.00%	ru	encr	0.9	1
Wood particle board	100.00%	ru	encr	0.9	1
Wooden frame	100.00%	ru	encr	0.9	1
Wooden parquet	100.00%	ru	encr	0.9	1
Wooden door with glass	100.00%	ru	d/nc	0.9	1
Wooden door	100.00%	ru	d/nc	0.9	1
Wooden door unit	100.00%	ru	d/nc	0.9	1
Wooden frame window 1.2*1.65m	100.00%	ru	d/nc	0.9	1
Wooden frame window 1.0*1.2m	100.00%	ru	d/nc	0.9	1

RU =Reusing
RC =(Recycling)
DCCR = Downcycling certified
ENCR = Energy Recovery certified
D/N=Disposal and non-certified

Material name (option 3)	MLP	SD	UD	FW	FV
Ceramic mortar glue	40.00%	rc	d/nr	0.9	0.7
Ceramic tiles	40.00%	rc	d/nr	1	0.7
Concrete	40.00%	rc	d/nr	0.6	0.9
Gypsum board	97.00%	rc	d/nr	0.9	0.6
Membrane	100.00%	rc	d/nr	0.9	0.7
Mineral wool	9.60%	rc	d/nr	1	0.6
OSB	85.00%	rc	encr	0.9	0.6
Steel mesh	100.00%	rc	rc	0.9	1
Steel plate 1mm	100.00%	rc	rc	0.9	1
Steel wire mesh	100.00%	rc	rc	0.9	1
Vapor barrier	0.00%	encr	d/nr	1	0.9

Wind barrier	0.00%	encr	d/nr	1	0.9
Wood cladding	95.00%	dccr	encr	0.8	0.6
Wood particle board	95.00%	dccr	encr	0.9	0.6
Wooden frame	100.00%	dccr	encr	0.8	0.6
Wooden parquet	95.00%	dccr	encr	0.8	0.6
Wooden door with glass	50.00%	rc	d/nc	0.9	0.8
Wooden door	50.00%	rc	d/nc	0.9	0.8
Wooden door unit	50.00%	rc	d/nc	0.9	0.8
Wooden frame window 1.2*1.65m	50.00%	rc	d/nc	0.9	0.8
Wooden frame window 1.0*1.2m	50.00%	rc	d/nc	0.9	0.8

RU =Reusing
RC =(Recycling)
DCCR = Downcycling certified
ENCR = Energy Recovery certified
D/N=Disposal and non-certified